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GRÜNERITE FROM ROCKPORT, MASSACHUSETTS, AND A SERIES OF SYNTHETIC FLUOR-AMPHIBOLES

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GRÜNERITE

In our thermal studies of iron silicates we have found the fayalite of Rockport, Mass., a very useful natural material, on account of its unusually close approach to the theoretical composition, Fe_2SiO_4 . The best fayalite from that source always has inclusions of grünerite, which we identified in an earlier paper. The refractive index $\gamma = 1.73$, then measured, is higher than that of any grünerite hitherto recorded and suggests that, like the fayalite, it is very close to the pure ferrous end-member of its series.¹ We have accordingly investigated it further and find that this suggestion is fully borne out by the facts.

Our first Rockport fayalite contained only a very small amount of disseminated grünerite, but upon examining other specimens in the collections of the U. S. National Museum we found that the fayalite was, in some examples, surrounded by a zone consisting almost entirely of grünerite. The specimens available do not show the relations of these minerals to the other minerals of the pegmatitic mass from which they were obtained, but an "anthophyllite" from this locality was described by Warren in 1903 in a brief preliminary note as follows: "Where the fayalite comes in contact with the quartz of the pegmatite, a reaction rim is developed consisting of radial fibrous aggregates. . . . The fibres are translucent, white to light brown in color, and at once suggest anthophyllite by their appearance." Warren then gives optical relations which indicate that it was an amphibole, apparently of orthorhombic symmetry.² Qualitative chemical tests showed it to be nearly pure iron

¹ Bowen, N. L., and Schairer, J. F., *Am. J. Sci.*, vol. 24, p. 201, 1932.

² Warren, C. H., *Am. J. Sci.*, vol. 16, pp. 339-342, 1903.

silicate. The description applies in all particulars to the material we have investigated except that ours is always monoclinic, with extremely fine polysynthetic twinning, and, therefore, to be classed as grünerite. Possibly in his brief preliminary examination Warren overlooked the fine twinning and we may be dealing with the same material. Indeed, an anthophyllite with nearly all the Mg replaced by Fe'' has not yet been definitely identified among natural minerals.

The best grünerite from this locality was found in the Roebling collection, now in the U. S. National Museum. It occurs as radiating, fibrous to asbestiform aggregates constituting a shell upwards of 1 cm. thick about masses of fayalite. It is pale gray to greenish-gray in color, though in places somewhat brownish from oxidation. The density, kindly determined by Dr. H. E. Merwin, is 3.597.

Under the microscope the fibres are found to be universally twinned after 100 and the twin bands are usually of hair-line width, a fact that renders the measurement of optical properties very difficult. The refractive indices, measured in immersion liquids in sodium light, are as follows: $\gamma = 1.729$, $\beta = 1.709$, $\alpha = 1.686$, all $\pm .002$. From these values the optic axial angle is calculated as $2V \text{ negative} = 86^\circ$ which is in general agreement with the direct observation of the interference figure though no great reliance is to be placed upon this on account of the fine twinning, nor, of course, is the calculated value of high accuracy because of the large possible error in refractive indices. The extinction angle $c \wedge \gamma = 10^\circ$.

CHEMICAL COMPOSITION OF ROCKPORT GRÜNERITE

A very satisfactory separation of the mineral from associated fayalite can be effected by hand-picking and when this is followed by magnetic separation of magnetite a substantially pure product is obtained. The analysis of this product is given in Table 1. It proves to be, as was expected, the nearest approach to the pure $\text{Fe}_7\text{H}_2(\text{SiO}_3)_8$ that has yet been encountered. The small amount of Fe_2O_3 is probably largely secondary, for it is impossible to avoid including some material that has been changed to a slightly brownish color. The MnO content is small and comparable with that

found in the associated fayalite. Fluorine is excessively low and the mineral may be regarded as a definite hydroxy-amphibole.

TABLE 1
CHEMICAL COMPOSITION OF GRÜNERITE

	I	II
SiO ₂	47.54	48.08
Al ₂ O ₃	0.20	—
Fe ₂ O ₃	0.71	—
FeO	47.25	50.13
MnO	2.14	—
MgO	0.04	—
CaO	none	—
Na ₂ O	0.29	—
K ₂ O	0.11	—
H ₂ O	1.55	1.79
F	0.01*	—
	<hr/> 99.84	<hr/> 100.00

I. Grünerite from Rockport, Massachusetts.

II. Theoretical $\text{H}_2\text{Fe}_7(\text{SiO}_3)_8$ or $(\text{OH})_2\text{Fe}_7(\text{Si}_4\text{O}_{11})_2$.

* Determined by E. S. Shepherd.

CUMMINGTONITE-GRÜNERITE SERIES

The establishment of the properties of the end-members of mineral groups is of especial value in systematic mineralogy. As an end-member of the cummingtonite-grünerite series it is of interest to compare the properties of the present grünerite with other members of this series. Sundius has collected the data for a number of representative amphiboles.³ Unfortunately when one attempts to correlate the properties with the composition it is necessary to make simplifying assumptions regarding the composition, certain constituents being neglected, and MnO, when present in small amount, being added to FeO. Accepting Sundius's simplified compositions but stating them with hydroxyl recognized as essential, we may present his data and ours as in Table 2.

³ Sundius, N., *Am. J. Sci.*, vol. **21**, p. 330, 1931.

Winchell, Kunitz, and others have made similar correlations but Sundius has been able to include their data.

TABLE 2
OPTICAL PROPERTIES OF THE GRÜNERITE-CUMMINGTONITE SERIES

Composition mol. per cent			α	β	γ	$\gamma - \alpha$	$2V_\alpha$	c/γ
$(\text{OH})_2(\text{Fe,Mn})_7$ $(\text{Si}_4\text{O}_{11})_2$	$(\text{OH})_2\text{Mg}_7$ $(\text{Si}_4\text{O}_{11})_2$							
A	100	0	1.686	1.709	1.729	0.043	86°	10°
1	90.5	9.5	1.672	1.697	1.717	.045	82°	10°-11°
2	77.5	22.5	1.666	1.684	1.704	.038	90°	14°
3	60.5	39.5	1.655	1.669	1.686	.031	93°	17°
4	42.5	57.5	1.639	1.648	1.667	.028	111°	20°
5	40.0	60.0	1.640	1.647	1.665	.025	115°	20°

A. Grünerite, Rockport, Mass.

1. Grünerite, Collobrières (La Mallière) France. Sundius, *Am. J. Sci.*, vol. **21**, pp. 330-344, 1931.

2. Grünerite, Cummington, Mass. Sundius, *Am. J. Sci.*, vol. **21**, pp. 330-344, 1931.

3. Grünerite, Bijiki, Marquette, Mich. Sundius, *Am. J. Sci.*, vol. **21**, pp. 330-344, 1931.

4. Cummingtonite, Rönnebygruvan, Sweden. Sundius, *Am. J. Sci.*, vol. **21**, pp. 330-344, 1931.

5. Cummingtonite, Persberg, Sweden. Sundius, *Am. J. Sci.*, vol. **21**, pp. 330-344, 1931.

In Fig. 1 the data of Table 2 are plotted and the curves (straight lines) therefore give the variation of refractive indices with composition in the cummingtonite-grünerite series in so far as these are determined by existing data on natural minerals. The curves are drawn so as to give particular weight to our especially pure end-member. It will be noted that when this is done the value of α for the Collobrières grünerite (No. 1, Table 2 and Fig. 1) lies well below the curve. The Collobrières mineral is, however, notably divergent in chemical composition from that strictly characteristic of the series in question. Indeed, it contains so much CaO , Al_2O_3 , Fe_2O_3 , and alkalis that only by courtesy can it be regarded as a member of the series.⁴ Its birefringence is too high for any member of the series, being somewhat greater than that of the very pure Rockport grünerite.

The other members plotted show a fairly close approach to the theoretical composition of a member of the series and the plot as a whole may therefore be regarded as giving a rather reliable picture of the variation of properties with composition.

⁴ An analysis of this grünerite is given by Kreutz, *Z. Kryst.*, vol. **49**, p. 210, 1910.

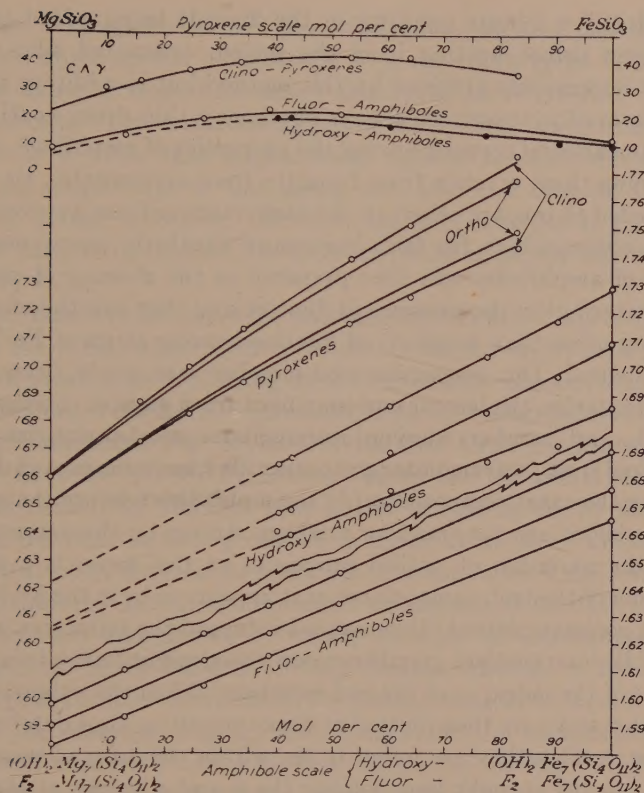


FIG. 1. Optical properties of Mg-Fe amphiboles and pyroxenes.

The curves of refractive indices have been drawn as broken lines at low-iron compositions. It may be that no such monoclinic hydroxy-amphiboles exist; certainly none has yet been found. As Sundius has emphasized, all such amphiboles now known are orthorhombic.⁵ This relation in the hydroxy-amphiboles is in strong contrast with that in fluor-amphiboles now to be described.

SYNTHETIC FLUOR-AMPHIBOLES

In our studies of the inversion of pyroxenes of the MgSiO_3 - FeSiO_3 series from the orthorhombic to the monoclinic form we found certain members (bronzites) very reluctant to invert. In order to induce the change we resorted to the use of NaF as a

⁵ Sundius, N., *Min. u. pet. Mitteil.*, vol. 43, pp. 422-440, 1933.

"catalyst," a minute quantity of the fluoride being added to the pyroxene before heating it in the sealed, evacuated silica-glass tube.⁶ Success was attained by this method but in addition to the new form of pyroxene we always obtained a thin drusy coating of minute euhedral crystals having the properties of amphibole. After obtaining these crystals from bronzite thus accidentally, we then proceeded to prepare others in the same manner from pyroxenes of other compositions (in fact from pure synthetic pyroxenes). A series of amphiboles was thus prepared in the absence of oxygen and water but in the presence of fluorine and they can therefore be nothing other than members of fluorine-bearing series of Fe'', Mg amphiboles.⁷ The magnesian end-member was made from pure clino-enstatite, the ferrous end-member from a glass of composition FeSiO_3 , and members having intermediate optical properties were prepared from intermediate pyroxenes. We have no means of determining the exact composition of the amphiboles because the quantities yielded are too small for analysis. Acting on the assumption that the variation of optical properties of this series is a linear function of the mol. composition, as it appears to be in the hydroxy-series, we have plotted the measured values of the refractive index, γ , of the intermediate members upon the straight line joining the values of the index, γ , of the end members. When the values of the indices β and α are then plotted at the composition thus determined by the γ value they are found to lie, within the error of measurement, on the straight lines joining the β and α values of the end members, as is shown in the resulting plot, Fig. 1, by the curves labelled "fluor-amphiboles."

The extinction angles of these synthetic amphiboles were also determined. They always show repeated twinning after 100, in the same manner as the natural grünerite, and the extinction was measured against the twinning. The members of intermediate composition always have higher extinction than do the end-members so that the extinction angle must pass through a maximum at some intermediate composition. If, again, it is assumed that the composition of the intermediate members is determined by the straight-line

⁶ Bowen and Schairer, *Am. J. Sci.*, vol. 29, p. 170, 1935.

⁷ It is possible that a little of the sodium of the NaF enters into the amphiboles but there is evidence that most of it combines with the silica glass tube. Attempts to make hydroxy-amphiboles in the same manner but with NaOH substituted for NaF gave only negative results.

relation of refractive indices discussed above, we may plot the extinction angle against composition with the result given in Fig. 1, in the upper section of the figure and in the curve labelled "fluor-amphiboles." The extinction angles of the hydroxy-amphiboles are shown in a curve that is practically parallel to this. Monoclinic hydroxy-amphiboles of this series with low iron content are, as already stated, unknown. The curve has been extended as a broken curve parallel to that for the fluor-amphiboles merely for its suggestive value.

The refractive indices of the fluor-amphiboles are, it will be noted, lower than those of the hydroxy-series. It has, however, been necessary to break scale in plotting them both on one diagram, otherwise the γ -values of the fluor-series would, in part, overlap the α -values of the hydroxy-series. The curve of α for the fluor-series is sensibly parallel to the curve of α for the hydroxy-series and the actual lowering of index resulting from the substitution of fluorine for hydroxyl is about the same as that produced in topaz by an equal amount of substitution of fluorine for hydroxyl. For the index γ the lowering is not uniform throughout the series on account of the fact that in the hydroxy-amphiboles a strong increase of birefringence is brought about by increase of iron content whereas in the fluor-amphiboles a much more moderate effect of that kind occurs.

To the diagram, Fig. 1, have been added for comparison the curves of refractive indices of the pyroxenes of the MgSiO_3 - FeSiO_3 series in both orthorhombic and monoclinic forms and also the curve of extinction angles of the monoclinic series which, like the

TABLE 3
OPTICAL PROPERTIES OF SYNTHETIC FLUOR-AMPHIBOLES

Composition mol. per cent		α	β	γ	$c \wedge \gamma$	Initial pyroxene mol. % MgSiO_3
$\text{F}_2\text{Mg}_7(\text{Si}_4\text{O}_{11})_2$	$\text{F}_2\text{Fe}_7(\text{Si}_4\text{O}_{11})_2$					
100	0	1.583	1.590	1.598	8°	100
87*	13	1.593	1.600	1.610	13°	84
73*	27	1.604	1.613	1.623	20°	68
62*	38	1.615	1.623	1.633	23°	47
48*	52	1.625	1.634	1.645	21°	26
0	100	1.665	1.676	1.690	12°	FeSiO_3 glass

* Probable composition assuming linear variation (see text).

fluor-amphibole curve, passes through a maximum at an intermediate composition.⁸

In Table 3 the optical properties of the fluor-amphiboles are given together with their probable compositions and the composition of the pyroxene from which each was produced.

GENERAL CONSIDERATIONS

Fluorine-bearing amphiboles have been prepared by various investigators but apparently always from mixtures of extremely complex character and they throw little light on the nature of amphiboles except to emphasize their complexity. In the recent work of Scheumann and Lüdke such very complex amphiboles were prepared, the novel feature being that the synthesis was carried out at atmospheric pressure.⁹ Closed tubes were used in the preparation of our amphiboles but our sole object was the exclusion of air and consequent maintenance of the iron in the ferrous state. We did not measure the pressure, and while it is possible that pressures moderately exceeding the atmospheric were built up in the tube we have no reason to believe that high pressure prevailed.

Examination of Table 3 shows that the amphibole produced by this method was always much more magnesian than the pyroxene from which it was produced. Even if the composition assigned to the amphibole is in each case only approximately correct this relation will still hold. We are not sure that the amphibole formed is that which is in equilibrium with the pyroxene, but it almost certainly differs from the pyroxene in the direction approaching equilibrium. It is of interest therefore to recall that, in the pure Mg, Fe pyroxenes and olivines, the pyroxene is always more magnesian than the olivine with which it is in equilibrium, a relation whose significance we have commented upon.¹⁰ In the series olivine, pyroxene, amphibole, which is a typical discontinuous reaction series, we appear to have, then, the general relation that each phase is more magnesian than that member of the preceding phase with which it is in equilibrium. In igneous rocks there is ordinarily a change of composition of the liquid whereby it becomes less magnesian and these three phases separating successively from the

⁸ See Bowen and Schairer, *Am. J. Sci.*, vol. 29, p. 198, 1935.

⁹ Scheumann, K. H. and Lüdke, W., *Berichte der sächsischen Akad. Wiss. Leipzig*, vol. 85, pp. 273-278, 1933.

¹⁰ Bowen and Schairer, *Am. J. Sci.*, vol. 29, p. 213, 1935.

liquid reflect that fact in their composition. But in a rock formed by recrystallization during a metamorphic episode and containing all three of these phases we should expect that the amphibole would be more magnesian than the pyroxene and the pyroxene, in turn, more magnesian than the olivine.

ACKNOWLEDGMENT

We are indebted to the U. S. National Museum, through the courtesy of Dr. W. F. Foshag, for permitting us to use the grünerite specimen that has been the basis of this study, to Dr. H. E. Merwin for his measurement of the density of the grünerite, and to Dr. E. S. Shepherd for his determination of fluorine.

IGNEOUS ASSIMILATION AND ASSOCIATED CONTACT METAMORPHISM IN THE VIRGINIA MINING DISTRICT, NEW MEXICO*

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ABSTRACT

The rocks of the Virginia mining district consist chiefly of basalt of Comanche (?) age intruded by late Cretaceous or early Tertiary granodiorite. The granodiorite generally has a dark border, as much as 20 feet thick, that contains much augite as well as a more calcic plagioclase and a great deal more magnetite than the main mass. The differences are interpreted as being the results of partial assimilation of the adjacent basalt, in accordance with Bowen's reaction principle. In addition, the basalt adjacent to the contact, in a zone as much as 15 feet thick, is metamorphosed to a rock that mineralogically is similar to the invading granodiorite. The metamorphism is believed to have taken place at a period slightly later than the stage of magmatic assimilation and to have been in general accord with the reaction principle.

INTRODUCTION

The Virginia mining district is in Hidalgo County, southwestern New Mexico, and occupies the northern part of the Pyramid Mountains, one of the isolated desert ranges typical of the Mexican Highland of the Basin and Range province. (See figure 1.) An investigation of the geology and ore deposits of this district was made by the writer during parts of 1931 and 1933 for the United States Geological Survey in cooperation with the New Mexico Bureau of Mines and Mineral Resources, and this paper describes some of the features observed. A detailed report on the district is in preparation.

The rocks of the Virginia district consist chiefly of basalt flows and associated intrusive plugs of volcanic breccia and of rhyolite, of Comanche (?) age, all intruded by a stock of porphyritic granodiorite. Figure 2 shows the areal distribution of the different rocks. The basalt occupies most of the area and extends southward under the Tertiary volcanic rocks that form the main part of the Pyramid Mountains. The base of the basalt is nowhere exposed, though the workings of one mine penetrate it vertically over 2,000 feet. The granodiorite is an irregular, horseshoe-shaped mass that has an exposed area of about 10 square miles. Outliers, generally close to

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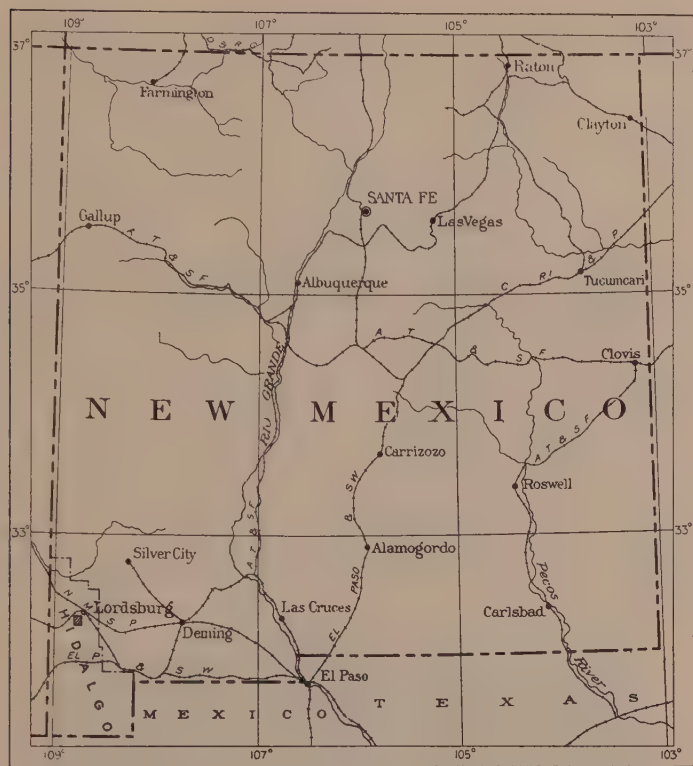


FIG. 1. Map of New Mexico. Shaded area shows location of the Virginia mining district, in Hidalgo County.

the main mass, are common and suggest that the stock may be appreciably larger at no great depth. The cover has been barely removed from the northern part of the stock, and the present topography in that part is very much like the original upper surface of the intrusion.

PETROGRAPHY

NORMAL ROCKS

Basalt.—The basalt is a soft, easily eroded rock that breaks into small angular pieces. It tends to be greenish in surface exposures but is dark gray to black as viewed underground. It is commonly aphanitic to faintly crystalline and contains a few phenocrysts of colorless augite, generally less than a millimeter long, in a ground-mass that consists of a felt of labradorite laths (about An_{60}) among

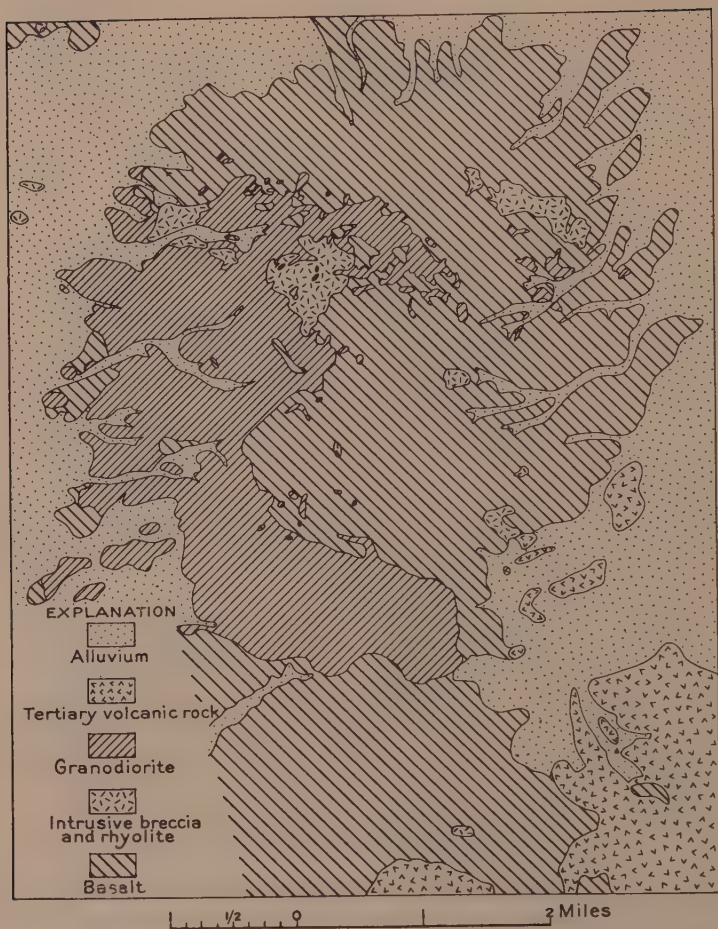


FIG. 2. Map showing areal distribution of major rock formations of the Virginia mining district, New Mexico.

which are scattered minute grains of augite and subordinate magnetite. The average composition is estimated to be about 50 per cent of feldspar, 35 per cent of augite, and nearly equal amounts of glass and magnetite.

Granodiorite.—The granodiorite is fairly uniform in texture and appearance throughout the main part of the mass. It is decidedly pink and contains as much as 40 per cent of plagioclase phenocrysts (about An_{30}), ranging from 1 to over 5 millimeters in length, a few phenocrysts of orthoclase, and several per cent of hornblende and

biotite in a granitic intergrowth of quartz and pink orthoclase, which are present in nearly equal amounts. Magnetite, titanite, apatite, and zircon are the accessory minerals. The magnetite is derived in part from resorbed and altered biotite and hornblende. The rock appears more porphyritic in thin section than would be supposed from the hand specimen.

BORDER-ZONE ROCKS

Granodiorite.—Locally at the borders of the stock, in a zone that ranges from a fraction of an inch to 20 feet in thickness, the granodiorite is much darker and is finer-grained than the normal rock. It is generally porphyritic, containing small phenocrysts of plagioclase and locally of ferromagnesian minerals. Quartz and orthoclase, one or both, are prominent at some places but scarce at others. Augite is present, ranging from a trace to about 15 per cent, as well as much more magnetite than characterizes the pink granodiorite. The augite seemingly is in two generations (as phenocrysts and in the groundmass), as in the basalt, and some of it is partly replaced by hornblende. The feldspars in some specimens

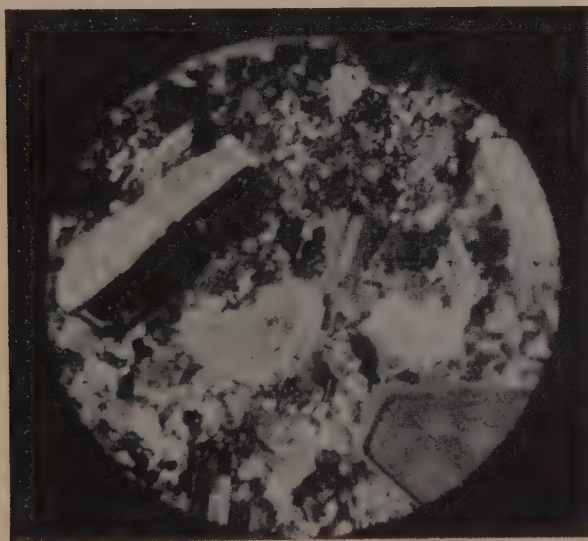


FIG. 3. Photomicrograph of dark granodiorite adjacent to included fragment of basalt. Nicols crossed. Shows zoning of the plagioclase in a single narrow band near the periphery of the crystals. Magnified 28 diameters.

contain included grains of augite, and in all specimens examined the plagioclase is about 10 per cent more anorthitic than in the main part of the stock. This basic border has been observed only where the granodiorite is in contact with basalt.

One specimen of granodiorite was collected that contained small inclusions of basalt only an inch or two across. The granodiorite adjacent to the inclusions, the contacts of which range from sharp to gradational, contains 5 to 10 per cent of augite, seemingly in two generations, as in the border rock and as in the basalt, and the plagioclase is zoned, the zoning in most crystals consisting of a single narrow calcic band near the edge of the crystal. (See figure 3.) The core and the periphery seem to be of about the same composition (An_{29}) as the plagioclase in the normal granodiorite; the calcic band is about An_{40} , the same as the plagioclase in the border facies.

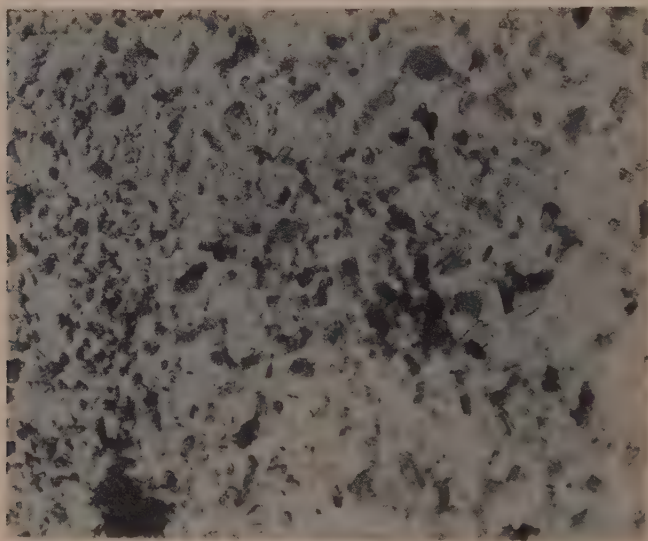


FIG. 4. Photomicrograph of metamorphosed basalt. Plain transmitted light. This rock originally was the same as that shown in figure 5. The abundant small dark crystals are crystalloblasts of biotite. The rest of the rock consists of a very fine-grained aggregate of orthoclase, plagioclase, and quartz. Magnified 56 diameters.

Basalt.—At those places where the granodiorite is marked by the dark border, the adjacent basalt for a distance of about 15 feet

or less differs considerably from the average rock. It is more coarsely crystalline and contains as much as 30 per cent of minute idiomorphic crystals of biotite and a few cumulophyric aggregates of the same mineral in a very fine-grained mosaic of orthoclase, oligoclase (An_{28}), and subordinate quartz. The original augite of the rock is represented by fibrous uralite, with which is usually associated a little magnetite. Figures 4 and 5 show the contrast between the original basalt and the metamorphosed rock. Other parts of the rock in the narrow alteration zone show an intermediate stage of modification; the augite is converted to an aggregate of pale-greenish fibrous amphibole, and the surrounding feldspathic groundmass contains patches and grains of orthoclase and quartz that appear to corrode the original material. The altered rock in this zone contains indistinct veinlets of orthoclase, quartz, and biotite and also larger irregular patches of the same material as much as an inch in diameter, and specimens of basalt containing metasomatic crystals of orthoclase and clusters of orthoclase and quartz have been collected 90 feet from any visible granodiorite contact.

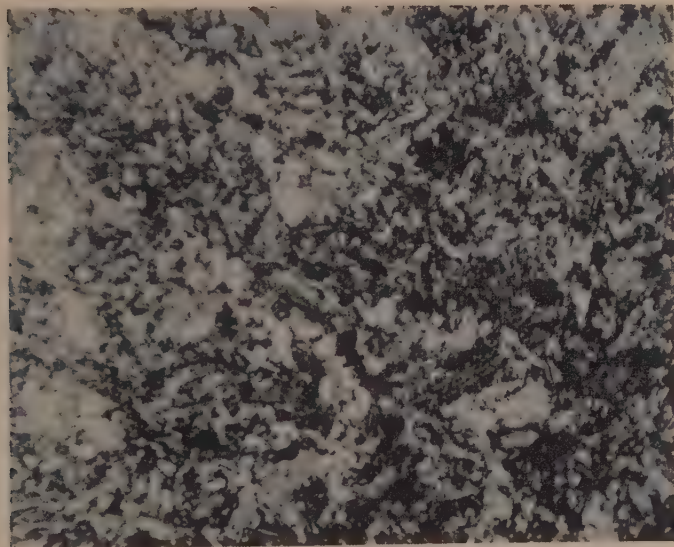


FIG. 5. Photomicrograph of the average basalt of the Virginia district. Nicols crossed. This photograph is in focus and shows the indistinctly crystalline felted intergrowth of the feldspar laths. Magnified 56 diameters.

At many places the weathered border-zone basalt is hardly distinguishable from the adjacent border-zone granodiorite.

DISCUSSION AND CONCLUSIONS

CHANGES IN THE GRANODIORITE

Three hypotheses have been advanced by petrologists to explain basic borders—that they originate (1) as the result of differentiation in place; (2) as a frozen sample of the original magma; and (3) as the result of assimilation of adjacent rock. The first two hypotheses seem to have nothing to recommend them in the Virginia district. On the contrary, they are actually opposed by some of the evidence. The basic borders have been observed only where the granodiorite is in contact with basalt, yet there would seem to be no reason why, under either of the first two hypotheses, there should not be a similar border against the intrusive rhyolite as well. Furthermore, there are thin basic borders against inclusions only an inch or two across, yet such small inclusions would hardly be expected to exert the degree of thermodynamic control required by both hypotheses. On the other hand, the differences between the basic border and the main mass seem to conform nicely with what would be expected from a partial assimilation of the adjacent basalt in accordance with Bowen's reaction principle.¹ According to this principle, foreign inclusions of augite and labradorite dropped into a magma from which hornblende and oligoclase were being precipitated would react with the liquid of the magma and would be converted into the minerals with which the liquid was saturated—the augite into hornblende, the labradorite into oligoclase. On casual consideration there seems to be a discrepancy between this expected ideal and the fact that the new plagioclase in the hybrid granodiorite of the Virginia district is more calcic than the plagioclase of the original granodiorite magma. But this discrepancy is apparent only. The composition of the plagioclase that is formed after equilibrium is reached depends upon the temperature, and the more calcic nature of the new plagioclase implies, therefore, a temperature increase in the border zone. Normally this may not be expected, but Bowen stresses the fact that reactions such as the conversion of labradorite to oligoclase and of augite to hornblende would yield heat

¹ Bowen, N. L., *The evolution of igneous rocks*, pp. 54–62; 173–223, Princeton Univ. Press, 1928.

to the system, and that if the withdrawal of heat were very slow these reactions "might result in actual rise in temperature and the establishment of equilibrium at a higher temperature where the plagioclase crystals would be more calcic."² The presence of plagioclase of composition An_{28} in the adjacent metamorphosed basalt would seem to indicate that the temperature there was close to that in the granodiorite—a condition that would have delayed withdrawal of heat from the assimilation zone.

Where only small inclusions of basalt were assimilated, the change in the composition of the new plagioclase was only temporary. In the specimen described above, which contained the zoned feldspar, the pieces of basalt were engulfed after crystallization of the normal plagioclase (An_{30}) had started. When assimilation began, a calcic border (An_{40}) was built upon the sodic nuclei. As the foreign lime was consumed the plagioclase gradually became more sodic, and the final material consisted again of the plagioclase characteristic of the unmodified granodiorite magma. The evidence verifies Bowen's prediction that the addition of foreign inclusions more calcic than the material in equilibrium with the liquid might result in a reversal of zoning.³

A second interesting feature is the complete assimilation of the plagioclase of the basalt as contrasted with only partial destruction of the augite. A fundamental part of the reaction principle is the idea that minerals early in the reaction series can be converted to minerals later in the series only by precipitation of large quantities of those minerals with which the reacting liquid is saturated, and that the degree of conversion, or "assimilation," depends upon the amount of liquid available. Bowen stresses this idea strongly, and in illustration he discusses in detail situations in which forsterite is added to the system anorthite-forsterite-silica,⁴ a system analogous to the natural system under discussion. In some situations the forsterite is assimilated completely, being converted to clinoenstatite as the liquid cools, but in others the liquid is exhausted before the forsterite is consumed, and the final mass consists of clinoenstatite, forsterite, and anorthite, the forsterite being "strewn about," to use Bowen's words, just as the partly assimilated augite grains are strewn about in the granodiorite of the

² Idem, pp. 187–188, 196.

³ Idem, p. 188.

⁴ Idem, pp. 194–195.

Virginia district. Assimilation of the augite and labradorite of the basalt could have taken place only if accompanied by precipitation of large amounts of plagioclase and hornblende, with which the reacting liquid was saturated, and we need conclude simply that the liquid was exhausted as the result of this precipitation before the augite was assimilated completely but not before the labradorite was. Many individual grains of augite could have been assimilated fully, and there would be nothing to indicate the fact. The small amount of augite in the hybrid granodiorite as compared with that in the basalt supports this suggestion.

METAMORPHISM OF THE BASALT

The crystalloblastic biotite-bearing rock is presumably a contact-metamorphosed basalt to which soda, potash, and silica were added. The changes that took place were evidently in general accord with the principle of reaction and were similar to those that occurred in the assimilation zone of the granodiorite, the tendency having been to convert the basalt into a rock like the granodiorite. The pyroxene was changed to amphibole, the plagioclase to less calcic plagioclase, and in addition biotite, orthoclase, and quartz were formed. The reactions are not considered as having been necessarily a continuation of those in the granodiorite, for it seems hazardous to assume that a reaction series can be carried from the complex but closed system of the magma into the independent and more complex open system of escaping emanations. As stated by Fenner,⁵

According to a simple principle of thermodynamics, in a system consisting of solid, liquid, and gas, if the solid and liquid are in equilibrium, also the liquid and gas, then the solid and gas must be in equilibrium. It follows directly from this that if we have a fluid magma through which gases are rising, and if these gases form volatile compounds with the mineral matter of the magma or bring it into the gaseous condition in any manner, then (provided that there is equilibrium) any minerals crystallizing in the liquid portions of the magma will have their counterpart in minerals depositing from the gases at the contact. . . .

With reference to actual magmas and the minerals formed by gases escaping from them, these principles have important applications. It is apparent that modifications of the ideal system are required, but there should be a strong tendency to reproduce in the contact rocks the same minerals that are crystallizing in the magma

⁵ Fenner, C. N., Ore deposits of western United States: *Am. Inst. Min. and Met. Eng.*, pp. 80-81, 1933.

Geologists do not agree on whether metamorphism is produced by gases or by liquids, but Fenner's conclusions would apply equally well for either.

The addition of soda, potash, and silica to the basalt suggests that the metamorphism occurred after the granodiorite had passed the plagioclase stage of pyrogenic crystallization—that is, at a period slightly later than the stage of magmatic assimilation of the basalt. If albite had been formed, or if there were any albitization of the oligoclase or of the original labradorite, there would be little reason to hesitate in accepting this suggestion and concluding that the metamorphism had taken place at a very early hydrothermal stage. That conclusion seems to be the most plausible for the general situation, regardless of the calcic nature of the new plagioclase, which may well be the result of a temperature control. It is necessary to assume only that the narrow zone in which metamorphism occurred had been heated to the approximate temperature of the adjacent magma before the altering emanations escaped.

ACKNOWLEDGMENTS

I am indebted to several persons, particularly to C. S. Ross, for a critical discussion of the problem and for assistance in preparing this manuscript.

FURTHER STUDIES IN THE PYROXENE GROUP

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Not many years ago mineralogists commonly considered that minerals were substances of simple and definite composition such that any correct mineral analysis could be represented by a simple formula. Innumerable formulas have been proposed for various minerals on the basis of this theory and many names have been created for such substances. Gradually we are learning that minerals vary a great deal in composition. When these variations in composition are continuous from that corresponding with some simple formula to that which must be represented by a different simple formula, it is still customary to consider that each simple formula represents a mineral, whereas, in fact, it represents only one limit in a continuous series of variation. It seems desirable, if not perhaps necessary, to revise our ideas so that our mineral names may correspond in meaning with the actual fact that minerals vary in composition through considerable ranges. It is doubtless true that the limits of variation need names in many cases, especially when these limits correspond with simple formulas. But it would probably lead to a decided improvement in the accuracy of our conceptions if we could discard the notion that these limits (or end-members of variation) are properly called minerals, and reserve that name for the entire series or system of variations. As a concrete illustration, every mineralogist will say that the composition of the common mineral called diopside is given by the formula, $\text{CaMgSi}_2\text{O}_6$; nevertheless, no sample of this common mineral has yet been found in nature which corresponds exactly with this formula, and the variation from it amounts to very considerable percentages in some cases. Furthermore, these variations may continue without interruption till the formula is no longer even approximately correct. Then it is customary to assume that the substance has some other simple formula (although again it may differ considerably from that formula) and a new mineral name is applied to it. Accordingly, one mineral passes into another mineral by continuous variation, according to our present nomenclature. This condition is a consequence of our idea that minerals must be simple compounds of definite formulas. Would it not be much better to abandon the false idea that minerals are compounds which can be expressed in simple formulas, and accept the idea which expresses the

facts, namely, that nearly all minerals vary in composition through considerable ranges? If that were done, many names now given to minerals would be assigned to end-members, or, if preferred, to a definite (but necessarily arbitrary) portion of the total range of variation. The idea that the composition of any mineral can be expressed in a simple formula is responsible for the fact that in not a few cases no name has yet been given to the entire range of possible variations, although that is the thing which is most appropriately considered to be a mineral. Accordingly, some well known minerals have no name, although the end-members have names. As an illustration, the system magnesite-siderite-rhodochrosite may be mentioned.

Diopside is an end-member of another variation system which has been called pyroxene, in the narrow sense of that term. Diopside varies continuously from $\text{CaMgSi}_2\text{O}_6$ to $\text{CaFeSi}_2\text{O}_6$ (called hedenbergite), and also to $\text{MgMgSi}_2\text{O}_6$ (called clinoenstatite), as well as nearly to $\text{FeFeSi}_2\text{O}_6$ (called clinohypersthene). It also seems to vary continuously to $\text{NaAlSi}_2\text{O}_6$ (called jadeite) and to $\text{NaFeSi}_2\text{O}_6$ (called aegirite). Finally, it varies by including alumina or ferric iron, but only in limited amount, and apparently by forming mix-crystals with $\text{AlAlAl}_2\text{O}_6$ or $\text{FeFeFe}_2\text{O}_6$ or both. In this case the substance (not the end-member) is called augite.

Not long ago it seemed probable that the maximum tenor of iron in pyroxene¹ could be expressed by the formula $\text{MgFeSi}_2\text{O}_6$, and consequently this formula was assigned as that of the end-member called clinohypersthene. However, Bowen² has shown that a much higher tenor of iron is possible in pyroxene in slags, one sample containing 70 per cent FeSiO_3 (disregarding magnetite and sphalerite present as inclusions, it is about 80 per cent FeSiO_3).

Bowen,³ Schairer, Posnjak, and Schaller^{3a} have also shown that the optical properties formerly attributed to hedenbergite (based on one determination) are incorrect.

For some purposes diagrams based on molecular proportions seem to be more useful than graphs based on proportions by weight.

Incorporating these changes, the relations between variations in composition and in optical properties in the clinoenstatite-diopside

¹ Winchell, A. N., *The New Mineralogy: Am. Mineral.*, vol. 18, p. 81, 1933.

² *Jour. Wash. Acad. Sci.*, vol. 23, p. 83, 1933.

³ *Am. Jour. Sci.*, vol. 26, p. 260, 1933.

^{3a} *Am. Mineral.*, vol. 14, p. 319, 1929.

series are shown in the first figure, which is based on the properties of pure artificial crystals as determined by Bowen.⁴ It is well known that these mix-crystals are not stable at low temperature, separating into crystals of diopside and enstatite.

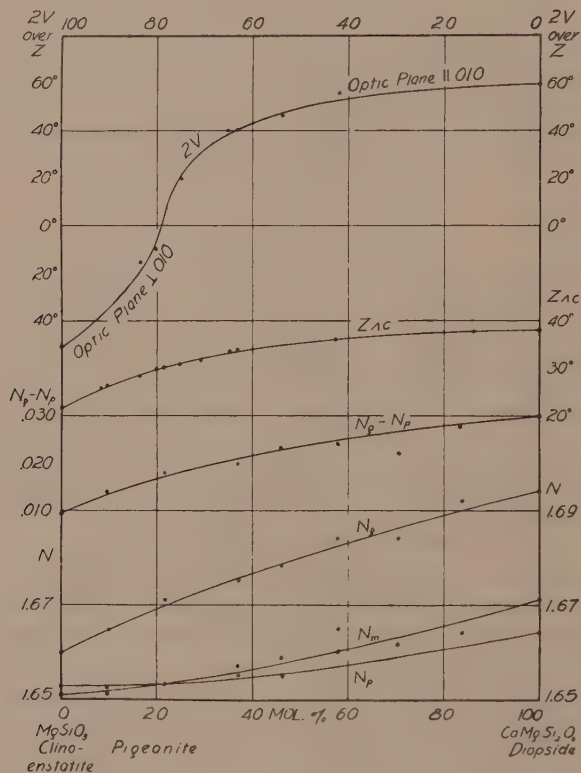


FIG. 1. Variations in composition and optic properties in the clinoenstatite-diopside series. Data of N. L. Bowen: *Am. Jour. Sci.*, vol. 38, p. 245, 1914.

The second figure shows the relations between variations in composition and optic properties in the diopside-hedenbergite series, including the corrected data for hedenbergite, as determined on artificial crystals,⁵ and also on natural crystals.⁶

⁴ *Am. Jour. Sci.*, vol. 38, p. 245, 1914.

⁵ For diopside: *Am. Jour. Sci.*, vol. 38, p. 245, 1914. For hedenbergite: *Am. Jour. Sci.*, vol. 26, p. 260, 1933.

⁶ For diopside-hedenbergite series: *Am. Jour. Sci.*, vol. 6, p. 511, 1923; vol. 26,

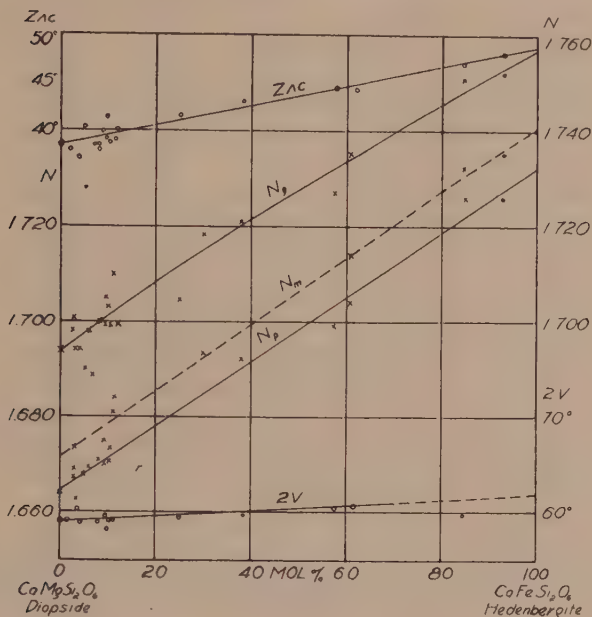


FIG. 2. Variations in composition and optic properties in the diopside-hedenbergite series.

The third figure shows the relations between variations in composition and in optical properties in the hedenbergite-clinohypersthene series, as determined on artificial crystals⁷ as far as 56 mol. per cent FeSiO_3 , with extrapolation guided by measures on a high-iron pyroxene found in a slag.⁸ In this case also the mix-crystals are not stable at low temperatures.

The fourth figure shows the relations between variations in composition and in optic properties in the MgSiO_3 - FeSiO_3 series of artificial monoclinic pyroxenes, as very recently determined by N. L. Bowen and J. F. Schairer.⁹

p. 260, 1933; *Am. Mineral.*, vol. **14**, p. 319, 1929. Hedenbergite from Heroult, Calif., has $N_g=1.752$, $N_m=1.735$, $N_p=1.726$ according to N. L. Bowen—personal communication, Oct. 23, 1934.

⁷ *Am. Jour. Sci.*, vol. **26**, p. 260, 1933.

⁸ *Jour. Wash. Acad. Sci.*, vol. **23**, p. 83, 1933.

⁹ *Am. Jour. Sci.*, vol. **29**, p. 151, 1935.

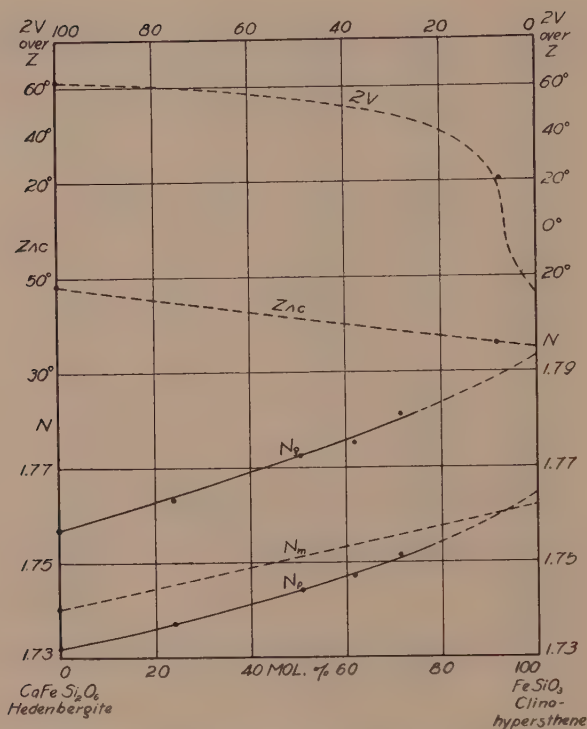


FIG. 3. Variations in composition and optic properties in the hedenbergite-clinohypersthene series. Data of N. L. Bowen, J. F. Schairer, and E. Posnjak: *Am. Jour. Sci.*, vol. 26, p. 260, 1933.

The fifth figure¹⁰ shows the relations between variations in composition and in optical properties in the entire clinoenstenediopsid-hedenbergite system. Under ordinary magmatic conditions mix-crystals containing more than about 50 per cent FeSiO_3 are quite unstable, and so this part of the diagram has no significance for rock-forming minerals; the upper left part of the diagram relates only to minerals of volcanic rocks, since the slow cooling of plutonic rocks leads to unmixing of these crystals. Hedenbergite is found chiefly in igneous contact zones and ore deposits, a mode of

¹⁰ T. Tomita (*Jour. Shanghai Sci. Inst.*, 1, 2, pp. 41-58, 1934) has recently published a similar diagram, but presents a part of the ternary system: CaSiO_3 - MgSiO_3 - FeSiO_3 as part of a triangular diagram.

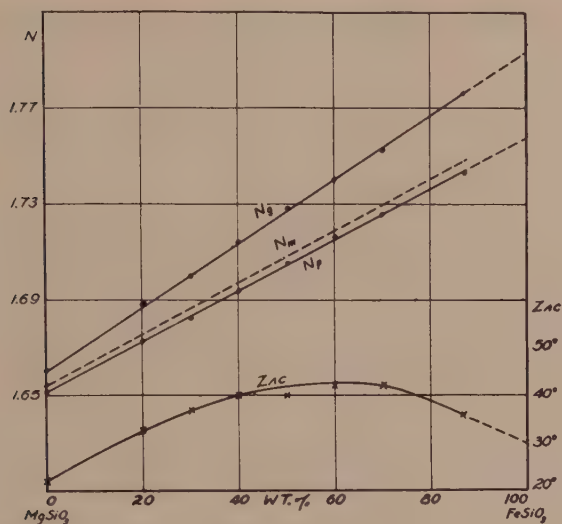


FIG. 4. Variations in composition and optic properties in the MgSiO_3 - FeSiO_3 series of monoclinic pyroxenes. N. L. Bowen and J. F. Schairer: *Am. Jour. Sci.*, vol. 29, p. 151, 1935.

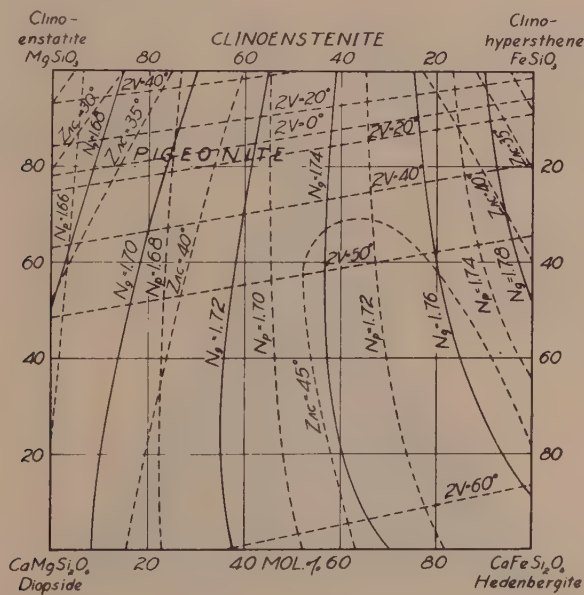
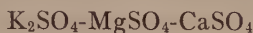


FIG. 5. Variations in composition and optic properties in the clinoenstenediopsid-hedenbergite system. Based partly on data of N. L. Bowen: *Am. Jour. Sci.*, vol. 38, p. 245, 1914, and vol. 26, p. 260, 1933.

occurrence which suggests crystallization at temperatures lower than those of most magmas. Pyroxenes belonging to this system and not close to the diopside-hedenbergite series in composition are rare,¹¹ but enough of them have been analyzed and optically measured to make it possible to sketch the curves showing the optic properties. But the correct position of these curves is known much less accurately than the correct position of the curves in the four (boundary) binary series given in the other diagrams. In spite of this fact, it may be stated with some confidence that monoclinic pyroxenes showing considerable variations in optical properties from those expressed in this diagram will be found to differ materially from this system in their composition, for example, by the presence of other pyroxene molecules, or of alumina, in crystal solution. On the other hand, monoclinic pyroxenes, which do not differ materially in optical characters from the properties shown in the diagram, will not differ materially in composition from the system represented. Also, it is already known that alumina has little effect on the optic angle and indices, but a considerable effect (causing an increase of about 3° to 5°) on the extinction angle.

¹¹ Examples follow: 1. Pigeonite, Onega Sea; W. Wahl: *T. M. P. M.*, vol. **26**, p. 27, 1907, with 51% Fe mol. and 43% Ca mol. $2V=23^{\circ}-40^{\circ}$, $N_g=1.740-1.742$, $N_m=1.719$, $N_p=1.716-1.718$, $Z\wedge c=45^{\circ}$. 2. Pyroxene, Marquesas; T. F. W. Barth: *Am. Jour. Sci.*, vol. **21**, p. 377, 1931, with 29% Fe mol. and 41% Ca mol. $2V=46^{\circ}$, $N_g=1.728$, $N_m=1.701$, $N_p=1.695$, $Z\wedge c=39^{\circ}$. 3. Pigeonite, Aland Island, W. Wahl: *T. M. P. M.*, vol. **26**, p. 18, 1907, with 39.5% Fe mol. and 17.5% Ca mol. $2V=16^{\circ}-20^{\circ}$, $N_g=1.711$, $N_m=1.691$, $N_p=1.690$, $Z\wedge c=44\frac{1}{2}^{\circ}$. 4. Augite, Ob. Veltlin; H. Küchler: *Chem. Erde*, vol. 1, pp. 58, 69, 70 (No. X), 1914, with 25.9% Ca mol. and 36.5% Fe mol., $N_m=1.7249$, $Z\wedge c=43^{\circ}$. 5. Pigeonite, Mull; A. F. Hallimond: *Mineral. Mag.*, vol. **17**, p. 97, 1914, with 57% Fe mol. and 9% Ca mol. $2V=0^{\circ}$, $N_g=1.744$, $N_m=N_p=1.714$, $Z\wedge c=40^{\circ}$. 6. Pyroxene from slag, N. L. Bowen: *Jour. Wash. Acad. Sci.*, vol. **23**, p. 83, 1933, with 92% Fe mol. and 8% Ca mol. $2V=20^{\circ}-25^{\circ}$, $N_g=1.785$, $N_m=?$, $N_p=1.745$, $Z\wedge c=36^{\circ}$.

AN X-RAY STUDY OF THE SYSTEM



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ABSTRACT

X-ray examination of fused mixtures of K_2SO_4 , MgSO_4 and CaSO_4 revealed a continuous isomorphous series with $\text{K}_2\text{Mg}_2(\text{SO}_4)_3$ and $\text{K}_2\text{Ca}_2(\text{SO}_4)_3$ as end-members. No other compounds were found. The members of this series are simple cubic, with four molecules in the unit cell, and the length of the cube edge varies from 9.96 Å for the Mg to 10.37 Å for the Ca end-member. The data from this system suggest an explanation concerning the extraction of K_2SO_4 from calcined polyhalite.

For several years the Nonmetallic Minerals Experiment Station of the U. S. Bureau of Mines, at New Brunswick, N. J., has been working on the extraction of potash from the mineral polyhalite, $2\text{CaSO}_4 \cdot \text{K}_2\text{SO}_4 \cdot \text{MgSO}_4 \cdot 2\text{H}_2\text{O}$. During the course of this investigation the writer has assisted by making x-ray examinations of various samples which have been submitted to him. Certain of these x-ray photographs, together with additional ones from samples prepared in our own laboratory, furnish considerable information concerning the system $\text{K}_2\text{SO}_4\text{-MgSO}_4\text{-CaSO}_4$. The compositions of the samples for which x-ray data were obtained are indicated in the diagram of figure 1. These samples were prepared either by fusion of the appropriate minerals, or by the fusion of molecular proportions of the individual sulfates. Since no single crystals were available, the powder method alone was used.

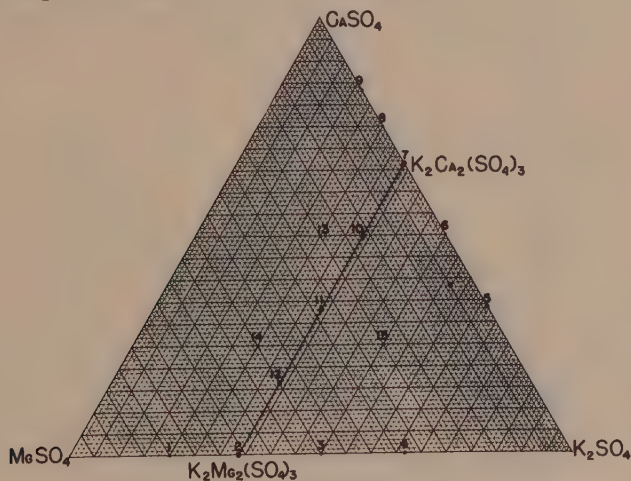


FIG. 1. Molecular compositions of samples studied.

In the system K_2SO_4 - $MgSO_4$ samples ranging in composition from 20 per cent to 66 per cent of K_2SO_4 were prepared (numbers 1-4). The only compound formed was $K_2Mg_2(SO_4)_3$. This corresponds in composition to the mineral langbeinite, and agrees with it in both optical¹ and x -ray data. As the composition shifts in either direction toward K_2SO_4 or $MgSO_4$, the lines of the $K_2Mg_2(SO_4)_3$ pattern remain unchanged, and additional lines of the corresponding simple sulfate appear.

The powder photographs of $K_2Mg_2(SO_4)_3$ indicate a cubic unit

TABLE 1
POWDER PHOTOGRAPH DATA FROM SYNTHETIC LANGBEINITE

Spacing in Å	<i>hkl</i>	Observed intensity	
4.07	112	m	$d_{100}=9.96\text{Å.}$ Four molecules $K_2Mg_2(SO_4)_3$ in unit cube. Calculated density 2.77. Natural langbeinite 2.83.
3.15	130	vs	
3.00	113	m	
2.77	230	m	
2.66	123	s	
2.40	{140}	m	
	{223}		
2.28	133	w	
2.16	124	w	
2.12	233	w	
2.03	224	w	vs=very strong s=strong m=medium w=weak
1.95	{134}	m	
	{150}		
1.85	{234}	m	
	{250}		
1.73	{144}	m	
	{225}		
1.61	{116}	ms	
	{235}		
	{126}		
1.55	{344}	w	
	{450}		
1.48	{245}		
	{360}	m	
1.42	236	w	
	{127}		
1.35	{255}	mw	
	{336}		

cell, containing four molecules, and having $d_{100}=9.96\text{\AA}$. (Table I). Since the reflections 112, 130, 230, 123, 140, 223, 124, and 233 are impossible for a face-centered cube, and 113, 230, 140, 223, 133, 124, 234 and 250 for a body-centered cube, the space lattice must be simple cubic. Powder photograph data alone are incapable of solving a structure as complex as this one. However, single crystals of the isomorphous $(\text{NH}_4)_2\text{Ca}_2(\text{SO}_4)_3$ have been obtained, and a determination of its structure is in progress. According to Dana, langbeinite is isometric-tetartohedral. This is confirmed by the crystals of $(\text{NH}_4)_2\text{Ca}_2(\text{SO}_4)_3$, which consist of the pyritohedron (210) in combination with a tetrahedron.

The system $\text{K}_2\text{SO}_4\text{-CaSO}_4$ is similar to the $\text{K}_2\text{SO}_4\text{-MgSO}_4$ (numbers 5-9). The only compound found was $\text{K}_2\text{Ca}_2(\text{SO}_4)_3$. Although this compound shows low double refraction,¹ the diffraction pattern is quite similar to that of $\text{K}_2\text{Mg}_2(\text{SO}_4)_3$, and agrees with a unit cube having $d_{100}=10.37\text{\AA}$.

No compounds could be found in the system $\text{CaSO}_4\text{-MgSO}_4$, nor are there any known hydrated double salts of these two sulfates.

A series of samples in the ternary system $\text{CaSO}_4\text{-MgSO}_4\text{-K}_2\text{SO}_4$ revealed that the two compounds $\text{K}_2\text{Mg}_2(\text{SO}_4)_3$ and $\text{K}_2\text{Ca}_2(\text{SO}_4)_3$ are the end members of an isomorphous series, in which the Mg_2 is apparently replaceable in all proportions by Ca_2 (numbers 10-12). The size of the unit cube increases with increasing Ca content, as is shown in table 2. The x -ray patterns show a continuous series, with no evidence of a definite compound $\text{K}_2\text{MgCa}(\text{SO}_4)_3$, such as dolomite in the $\text{CaCO}_3\text{-MgCO}_3$ system. Complete replacement of magnesium by calcium, such as is here found, is very unusual.

TABLE 2

INCREASE IN SIZE OF UNIT CELL WITH INCREASING CALCIUM

$\text{K}_2\text{Mg}_2(\text{SO}_4)_3$	$d_{100}= 9.96\text{\AA}$.
$\text{K}_2(\text{Mg}_{3/2}\text{Ca}_{1/2})(\text{SO}_4)_3$	10.05
$\text{K}_2\text{MgCa}(\text{SO}_4)_3$	10.15
$\text{K}_2(\text{Ca}_{3/2}\text{Mg}_{1/2})(\text{SO}_4)_3$	10.24
$\text{K}_2\text{Ca}_2(\text{SO}_4)_3$	10.37

The x -ray patterns obtained from the calcium end of this series are of poorer quality than those from samples higher in magnesium. The lines are more diffuse, and not as many are present on the films. This fact, together with the double refraction, may indicate

that through the introduction of the larger calcium atoms, the structure is in a strained condition. That this structure is a reasonably stable one, however, is shown by the fact that this compound can be formed by the dehydration of syngenite, $\text{K}_2\text{SO}_4 \cdot \text{CaSO}_4 \cdot \text{H}_2\text{O}$ at 400°C . The pattern of this dehydrated material is identical with that of fused syngenite (number 6), both consisting of the lines of $\text{K}_2\text{Ca}_2(\text{SO}_4)_3$ and CaSO_4 .

Sample number 13 represents the composition of dehydrated polyhalite. The pattern in this case consists of the lines of $\text{K}_2\text{CaMg}(\text{SO}_4)_3$ and CaSO_4 . This is no confirmation of the existence of a definite compound with Ca and Mg in equal proportions. Since CaSO_4 is present in excess in the polyhalite, it crystallizes out as anhydrite, and the composition of the remainder drops until it intersects the line of the isomorphous series (figure 1). Likewise for samples 14 and 15, the patterns consist of the lines of $\text{K}_2\text{CaMg}(\text{SO}_4)_3$ with those of K_2SO_4 and MgSO_4 , respectively. Thus all stable compounds in the range studied lie on the line joining the two compounds.

THE DEHYDRATION OF POLYHALITE

Many experiments have been carried on to determine the optimum conditions for the extraction of potash from polyhalite.^{2,3,4,5} Polyhalite loses its water of crystallization rather suddenly at a temperature above 300°C . It has been found that when it is calcined at a temperature of about 475°C . for a short time, a product of low density is formed, from which almost complete extraction of K_2SO_4 and MgSO_4 is obtained with hot water. The CaSO_4 residue is peculiar in that it is rapidly converted to gypsum when treated with cold water. This latter phenomena suggested the possibility of the residue being "soluble" anhydrite, but x-ray photographs show it to be normal anhydrite.

If the polyhalite is calcined at a higher temperature, or for a longer time, the product is more dense, and the percentage of extraction is lower. A still higher density and a lower yield is obtained from fused polyhalite. As stated previously, the fused product consists of isotropic $\text{K}_2\text{CaMg}(\text{SO}_4)_3$ and CaSO_4 .

The initial problem in this study was to determine what differences exist between the properly calcined, over-calcined, and the fused polyhalite. Powder photographs of all three are practically

identical. Slightly sharper patterns are obtained from the fused material, and some of these films showed a few weak lines which were either not present or rather doubtful in the films of the calcined samples. This indicates a difference in the perfection of crystallization rather than a variation in structure or composition.

When polyhalite is dehydrated, there is a loss of water and a consequent decrease in density. At some stage, whether at complete dehydration or not is not known, the structure becomes unstable, and breaks down into $\text{K}_2\text{CaMg}(\text{SO}_4)_3$ and CaSO_4 . At the initial stage the material consists of porous dehydrated grains, composed of an intimate mixture of sub-microscopic crystallites of the two decomposition products. When this is treated with hot water, the $\text{K}_2\text{CaMg}(\text{SO}_4)_3$ dissolves, leaving a skeleton of CaSO_4 , on which is redeposited the CaSO_4 which went into solution as part of the $\text{K}_2\text{CaMg}(\text{SO}_4)_3$.

The formation of two distinct compounds from the polyhalite when dehydrated, implies an actual migration of atoms and a recrystallization. The velocity of such a reaction should increase with temperature. With increased temperature (or time) the larger crystallites will grow at the expense of the smaller, forming a more coarsely crystallized and a more dense material. Such changes might reasonably be expected to cause poorer yields on extraction with hot water. Actual fusion, resulting in well-formed crystals of anhydrite in a dense groundmass of $\text{K}_2\text{CaMg}(\text{SO}_4)_3$, gives a product with a still lower yield.

It might be possible to carry out this process so slowly that the intermediate stages of dehydration, decomposition and recrystallization could be separated. But under ordinary conditions the exteriors of the grains probably have decomposed and possibly recrystallized before the interiors are completely dehydrated. Accordingly the optimum conditions for calcination are those that give most decomposition with least recrystallization. These same conditions would likewise give the most porous and minutely crystalline residue of CaSO_4 , and therefore most easily converted into gypsum by cold water.

This interpretation is in harmony with such observations as are obtainable by microscopic study, and also agree with the increase in sharpness of the diffraction patterns from the fused samples over those from the low temperature calcines.

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IDENTIFICATION OF THE COPPER ORE MINERALS BY MEANS OF X-RAY POWDER DIFFRACTION PATTERNS¹

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PRESENT METHODS OF MINERAL INVESTIGATION

The technique of producing good polished sections of ore minerals is now well developed, and the methods of mineral identification are highly advanced. The minerals are examined in polished section by means of the reflecting microscope. This will probably continue to be the most convenient means for the study of opaque minerals, since, in general, mineral identification is rapid and fairly accurate, and mineral textures, which are of the utmost importance, may also be observed. Micro-chemical and etch tests are used in this work, aided by the polarizing microscope and observations of color, internal reflection, hardness, magnetism, and special properties. Tables for mineral identification based on the foregoing tests have been written by Murdoch (45),² Davy and Farnham (19), Farnham (21), Schneiderhöhn and Randohr (60), and Short (61).

Although the majority of minerals can now be determined by the methods commonly in use, the rare minerals in particular are still difficult, and occasionally impossible, to identify. The same is often true of minerals present in minute grains. In the latter case their general appearance seems to be modified by their surroundings, and the reagents, which will be in contact with more than one mineral, may bring about electrolytic effects which will completely change the expected reactions, causing incorrect identifications. Since mineral identification is essential in economic geology, any method which promises improvement of results is well worth use and further development. Such a method of accurate determination is possible by the use of x -ray powder diffraction data, a fact pointed out by Kerr (41) as long ago as 1924.

POWDER DIFFRACTION METHOD

A small amount of a powdered crystalline mineral placed in a beam of x -rays will produce a characteristic line or ring pattern on

¹ Abstract of a dissertation submitted to the Division of Geological Sciences of Harvard University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

² In order that the footnotes may be shortened all numbers in parentheses refer to the complete bibliography at the end of this article.

a photographic film. The possible use of this method for mineral identification has long been appreciated and its greater use predicted. Physicists and mineralogists have used the method, in conjunction with other types of *x*-ray studies, primarily in the working out of atomic structures of minerals. The Geophysical Laboratory has employed this method effectively in the study of solid solution series in artificial melts. The gradual change in spacing of the lines on the records may often be observed as the composition of the melt is changed gradually from one end member to the other. These records can be used to determine, by comparison, the composition of unknown members of the same series. Some use has been made of the diffraction method purely for purposes of mineral identification (66); but the data for such work is available in relatively few places, and lists of diffraction data arranged in tables which would allow the general worker to make identifications of unknown minerals by this method are not yet published. The metallurgists, working also with opaque compounds, are far ahead of the economic geologist in their appreciation and use of this tool for mineral identification.

A few, however, have recognized the use of *x*-ray diffraction patterns as an aid to the economic geologist. In 1924 Kerr (41) published an article in which he pointed out the use of this method in mineralographic work, and explained the technique to be used. Here also he reproduced a few of his *x*-ray records and explained their calculation and interpretation. He did not, however, give any table of data by means of which the identification of unknown minerals can be made.

It is not necessary to know the complete theory of *x*-ray production or of *x*-ray analysis of crystal structure in order to make use of the powder method simply as a means of identification. The powder method also lends itself admirably to polished section study, since any mineral dug or drilled from such a section must of necessity be in the powdered form, and under the microscope very pure material may be secured. In addition to identification of distinct species, it is possible, by use of the accurate apparatus now available, to determine the end members of isomorphous series, and, under favorable conditions, to make some estimate of the composition of intermediate members of the series. Finally, under proper manipulation and control the method leads to results having a high degree of dependability.

SCOPE AND PURPOSE OF INVESTIGATION

Because of the advantages just enumerated, this method was adopted by the writer in the hope of advancing the general technique of ore mineral identification. It was decided to start with the investigation of the copper ore minerals, and in the time available it has not been possible to extend the study generally outside that group. It is hoped that similar tables for the remainder of the ore minerals may in time be added to the material now presented. The usefulness of this table will be greatly diminished until that is done. Most of the non-opaque copper minerals are rare in occurrence and may be identified more readily by means of the petrographic microscope than by x -ray patterns. Therefore, only the minerals in this group which are occasionally important as ores are here included.

As originally planned, this article contained a résumé of the theory of x -ray powder diffraction, and the technique necessary in order to secure good photographs, in addition to the method of indexing herein proposed and the tables here presented. It was hoped, thereby, to prepare one short article, the use of which would enable one to prepare his material, photograph it, read the record, and, finally, to identify it. Because of the lack of space and the fact that many good articles on the theory and technique are available, only the method of indexing and the tables are here presented. The articles which best cover the theory and technique of x -ray powder diffraction work include Kerr (41), Bragg and Bragg (9), Wyckoff (68), Clark (14), and Davey (18).

ACKNOWLEDGMENTS

The writer is indebted to many for suggestions and assistance in this work, especially to members of the Division of Geology and Metallurgy at Harvard. The need of further x -ray work on known ore minerals, and the organization of these and older data into a serviceable table for mineral identification was pointed out by Mr. Harry Berman of the Department of Mineralogy. He encouraged the writer to undertake the problem and gave advice and guidance during the progress of the work. Both he and Professor Charles Palache were most generous of their time in securing specimens for this study. Professor L. C. Graton helped to make the x -ray work possible, gave encouragement and advice in its progress, and placed at the writer's disposal the large collection of polished sec-

tions which permitted microscopical identification of the minerals and insured the procurement of pure material for the tests. Dr. H. H. Lester of the Department of Metallurgy gave abundantly of time and advice in the immediate technique of manipulation, and Professor Albert Sauveur of the same Department generously allowed the use of the x -ray equipment. Dr. L. S. Ramsdell, Dr. Wm. Foshag, Dr. Paul F. Kerr, and Mr. Samuel Gordon kindly furnished material, data, or advice. To all of these the writer is indebted and wishes to express his thanks and appreciation.

CHARACTERISTICS OF RECORDS

To be of any use in the classification here outlined a record should show at least six well distributed lines, that is, lines produced through an angle of about 30° . If the record is one composed of many closely spaced lines, then eight or ten lines produced through an angle of 15° to 20° are sufficient. Only very doubtful identifications can be made with fewer data.

There are two characteristics in each record which are noted when it is read and which are here used in its classification. The first of these is the calculation in Ångstrom units of " d " (the interplanar spacing) for each line on the film, the second is the estimation of the intensity of each line. The values of " d " are written in numerical order from the highest, the line closest to the undeviated beam (zero line), to the lowest, the line most distant from the origin (Fig. 1). The intensity of the lines is indicated on a relative scale as follows:

- s—strong
- m—medium
- w—weak
- vw—very weak
- ew—exceptionally weak

It is not now possible to use a numerical scale, each number of which represents an absolute intensity, because the same mineral will not show the same absolute intensity of lines on any two records. This is because the absolute intensity of the lines produced by a given mineral depends upon so many variables. Since some of the conditions which determine intensity of lines vary in different mountings of a mineral, the absolute intensities of the lines must also vary in different diffraction patterns of the same mineral. However, the relative intensities of the lines are fairly constant, although in a few cases lines of practically equal intensity are inter-

changeable in the relative scale. Because of these conditions the strongest line on any film is marked "s", and the rest are labeled in relation to this line. By this method, even in poor films, the few lines that do show retain their relative ratings.

METHODS OF INDEXING

Three methods of indexing the minerals are used in this work. In the first method (Index 1), the records are listed in decreasing numerical order of the reading for the first line, namely, the line with the largest interplanar spacing "*d*". In any two records in which the reading for the first line is identical, the record with the higher reading for the second line is listed ahead of the other record. The complete record for each mineral will be given in this index. Accompanying this index is a plate of drawings of the corresponding records, arranged in the same order.

In many records the first one or more lines are weak to exceptionally weak, and therefore may not appear on poorer films. On the other hand very good records might pick up exceptionally weak lines, closer to the zero line, which are not shown on the writer's records. Under such conditions indexing on the basis of the first line shown could not in all cases be depended upon. Therefore, a second method of indexing has been adopted. In this second index the three or four most intense lines are taken from each record and arranged in order of their relative intensity. These lines are the ones certain to appear on any record of value. The records are then again arranged in a numerical sequence, beginning with the record having the highest value of "*d*" for its most intense line, and progressing to the record showing the lowest "*d*" for its strongest line. Where records have identical readings for the strongest line the reading for the next most intense line is also used for determining the order. In cases where the most intense lines are so nearly equal as not to be safely distinguished in intensity, or where the relative intensity of lines for the same mineral may vary in different photographs, the record is listed in each of its possible places. This index gives the reference to the position in Index 1 which has the complete record for the mineral, as well as to the drawings of the corresponding record.

In the third index the minerals are arranged alphabetically by their mineral names, reference again being given to the complete record in Index 1.

ERROR IN READING OF RECORDS

One should keep in mind the fact that in reading and indexing these records there is a maximum error of five in the last decimal place for each line recorded. Therefore, a deviation to this extent must be permitted when comparing a given record with the index. In the case of solid solution minerals there will be a gradual spreading of the characteristic distances ("d") of the lines as the composition changes from one end member to the other. This is well illustrated by the work of Machatschki (42, 43) on the tetrahedrite-tennantite group. He finds that tennantite, the arsenic member of the series, has the smaller unit cell. As antimony replaces the arsenic, or as silver replaces the copper, the size of the unit cell increases. This is exactly what would be expected, since the atomic radii of silver and antimony are larger than those of copper and arsenic, respectively. As the cell size is changed by the variation in composition, the powder diffraction pattern varies accordingly in the spacing of its lines. The powder photograph is therefore characteristic not only of the mineral group, but also of a mineral in this group having a particular composition. If this variation of the record, due to chemical change, is greater than the aforementioned error in reading the record, the various members of such a series may be determined. If the variation is less than that error, such a determination is not possible.

ILLUSTRATIONS

The method of using the first two tables may be illustrated with sodium chloride, the standard used in this work for calibrating all records (Fig. 1). The complete record for sodium chloride follows:

No.	Intens.	"d," Å.	No.	Intens.	"d," Å.
1	vw	3.25	9	m	1.149
2	s	2.81	10	w	.995
3	s	1.990	11	w	.938
4	ew	1.696	12	w	.890
5	m	1.625	13	w	.848
6	w	1.407	14	ew	.812
7	ew	1.291	15	vw	.780
8	m	1.258	16	vw	.752

This will occur in Index 1 at the place in the sequence where 3.25 comes, which is entry No. 30.

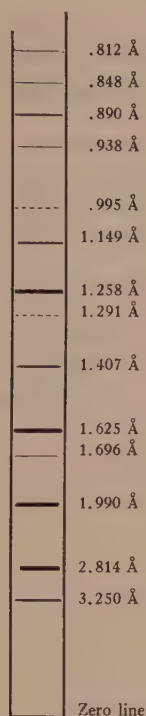


FIG. 1.

The record of the five most intense lines, in order of their intensity, is:

Intens.	"d," Å.
s.....	2.81
s.....	1.990
m.....	1.258
m.....	1.625
m.....	1.149

This will occur in Index 2 at the place in the sequence for 2.81.

This record would also be listed in Index 2 in the following order, since the first two lines are of about equal intensity (Fig. 1):

Intens.	"d," Å.
s.....	1.990
s.....	2.81
m.....	1.258
m.....	1.625
m.....	1.149

This will occur in Index 2 at the place in the sequence for 1.99.

Finally, in Index 3, reference to the complete record for sodium chloride is given at its proper alphabetical position.

INDEX 1

Records listed in decreasing numerical order of the reading for the first line, i.e. the line with the largest interplanar spacing, "*d*".

EXPLANATION OF TABLES

Small letters=Intensity symbols.

Number above columns=Number of the entry.

For *x*-ray photographs corresponding to these records see plate of line drawings.

1	2	3	4	5
Malachite (11)	Atacamite	Chalcanthite (25, 6)	Kröhnkite	Brochantite
vw 5.90	ew 1.955	s 5.40	vw 5.40	m 5.35
m 5.00	vw 1.900	s 4.67	vw 4.09	s 3.91
s 3.67	ew 1.780	s 3.96	vw 3.67	m 3.20
s 2.84	m 1.680	s 3.69	w 3.25	w 2.93
m 2.76	vw 1.636	m 3.28	ew 3.17	ew 2.82
m 2.51	vw 1.607	w 3.02	vw 3.08	m 1.563
vw 2.46	w 1.585	w 2.82	s 2.90	m 1.537
vw 2.41	vw 1.563	m 2.74	s 2.74	s 2.52
vw 2.32	ew 1.502	m 2.65	ew 2.59	m 2.47
vw 2.29	w 1.467	m 2.41	ew 2.64	w 2.39
ew 2.23	vw 1.945	vw 2.13	vw 2.58	vw 2.30
w 2.17	ew 1.381	ew 1.125	w 2.28	vw 2.27
vw 2.12	vw 1.352	w 2.02	ew 2.20	m 2.19
w 2.06	ew 1.164	w 1.975	ew 2.12	w 2.14
		ew 1.890	ew 2.06	w 2.08
		ew 1.845	vw 2.00	vw 2.01
		ew 1.818	ew 1.960	w 1.965
		vw 1.770	ew 1.920	vw 1.918
		w 1.625		vw 1.885
				w 1.822
				w 1.787
				ew .904
				ew .819

6			7			8			9			10		
Azurite (10)			Boleite ³ (23, 24, 30)			Bourbonite (49)			Linarite			Domeykite ⁴ (44, 58, 40)		
s	5.20	vw	1.430	vw	5.10	w	1.847	ew	4.70	m	1.845	ew	3.90	
s	3.67	vw	1.380	ew	4.86	m	1.798	vw	4.32	m	1.763	ew	3.03	
s	3.53	vw	1.353	s	4.40	w	1.747	vw	4.09	ew	1.723	ew	2.56	
vw	3.10	w	1.293	s	3.83	vw	1.670	m	3.86	w	1.660	ew	2.40*	
vw	2.94	vw	1.257	m	3.50	ew	1.612	w	3.68	w	1.625	m	2.14	
vw	2.82	vw	1.233	ew	3.34	vw	1.525	ew	3.25	ew	1.588	m	2.69	
s	2.54	vw	1.194	s	3.13	ew	1.475	m	2.96	w	1.555	s	2.04	
w	2.35	ew	1.173	vw	2.95	ew	1.417	w	2.89	ew	1.481	m	1.958	
m	2.28	ew	1.151	w	2.83	ew	1.350	m	2.81	ew	1.450	s	1.878	
m	2.24	ew	1.123	s	2.69	ew	1.321	s	2.73	w	1.421	ew	1.563	
vw	2.18	ew	1.108	m	2.56	vw	1.290	m	2.67	ew	1.388	vw	1.308	
vw	2.12	ew	1.071	ew	2.47	ew	1.262	m	2.58	ew	1.360	vw	1.217	
ew	2.02	ew	1.051	s	2.38	ew	1.237	ew	2.47	ew	1.332	ew	1.186	
m	1.945	ew	1.025	s	2.32	ew	1.200	vw	2.37	ew	1.250	m		
ew	1.900	ew	1.001	ew	2.15	ew	1.168	ew	2.29	ew	1.227	ew		
m	1.825	ew	.975	ew	2.12	ew	1.139	ew	2.22	ew	1.145	ew		
w	1.785	ew	.943	ew	2.07	ew	1.091	vw	2.09	ew	1.106	w		
ew	1.700	vw	.931	ew	2.02	ew	1.32	m	1.980	ew	1.080	m		
ew	1.645	ew	.913	m	1.985	ew	.981	m	1.945			vw		
w	1.593	ew	.893	ew	1.900	ew	.920					ew		
vw	1.560	ew	.868	vw								ew		
w	1.513	vw	.835	w								ew		
vw	1.480	vw	.818	vw										

³ This record does not check either isometric or tetragonal structure if the size of the unit cell is that given in the references.

⁴ A good record is difficult to obtain.

* This line is not present in records obtained by the writer, but is in the record kindly sent by L. S. Ramsdell.

11	12	13	14	15	16	17
Antlerite	Cubanite (Chalmersite)	Ag I ⁵ (4, 5)	Miersite ⁵ (2, 4, 5)	25% CuI ⁵ 75% AgI (4, 5)	38% CuI ⁵ 62% AgI (4, 5)	Chalcostibite
s 3.85 m 1.733	ew 3.84 ew 1.494	3.75	w 3.72	3.675	3.63	vw 3.63
w 3.17 ew 1.701	w 3.48 ew 1.461	3.24	s 3.23	3.186	3.14	s 3.10
ew 2.90 ew 1.668	m 3.21 ew 1.440	2.29	m 2.28	2.250	2.22	s 2.98
ew 2.80 vw 1.628	s 3.07 ew 1.356	1.966	m 1.948	1.920	1.893	vw 2.54
m 2.66 vw 1.591	vw 2.78 ew 1.313	1.873	ew 1.489	1.838	1.812	m 2.29
s 2.51 w 1.558	vw 2.52 ew 1.275	1.622	ew 1.320	1.593	1.570	w 2.23
m 2.45 w 1.532	w 2.31 ew 1.249	1.489	ew 1.290	1.461	1.440	m 2.11
vw 2.37 w 1.500	m 2.12 ew 1.190	1.451		1.424	1.404	w 1.888
w 2.18 ew 1.454	m 1.937 ew 1.161	1.325		1.300	1.281	m 1.818
w 2.13 ew 1.425	m 1.890 ew 1.077	1.249		1.226	1.208	s 1.751
ew 2.07 ew 1.400	m 1.858 ew 1.056	1.147		1.126	1.110	ew 1.684
ew 2.00 ew 1.337	w 1.803 ew 1.021	1.086		1.077	1.061	w 1.613
ew 1.949 ew 1.311	m 1.745 ew .871	1.026		1.062	1.047	vw 1.547
w 1.810 ew 1.260	w 1.620 ew .857	.990		1.007	.993	w 1.435
	vw 1.541	.979		.971	.957	ew 1.344
				.961	.947	ew 1.309
						vw 1.286
						ew 1.258
						ew 1.226
						ew 1.198
						ew 1.159
						vw 1.139
						ew 1.068
						ew 1.006
						ew .981
						ew .870

⁵ Records 13, 15, 16, 18, and 23 are based on the work of Barth and Lunde (4, 5). The values of "*d*" listed above were calculated by the writer, and since no photographs of this series were made in this work, no intensities are listed. The approximate composition of members in the above series may be determined by comparison with these columns. The mineral miersite, number 14, was run by the writer. This mineral happens to be closer to pure AgI than to the theoretical composition listed in the texts. Mineral number 21 was supposed to be marshite. By its record it may be seen that it is not pure CuI, but contains some AgI. This whole series has patterns similar to those of sphalerite, colusite, and germanite. The variation in size of the unit cell in the CuI-AgI series is large, so that the various members may be identified; but even so the size of the unit cell in colusite, germanite, and sphalerite is different still, and so will not be confused, as the values of "*d*" will also differ.

18	19	20	21	22	23	24	25
50% CuI ⁵ 50% AgI (4, 5)	Umangite	Eucairite (57)	Marshite ⁵ (2, 73) (4, 5, 15)	Penroseite ⁶	Pure CuI ⁵ Marshite (4, 5)	Connellite	Chrysocolla ⁷
3.57	m 3.56	w 3.54	s 3.52	ew 3.49	3.49	ew 3.40	s 3.35
3.095	m 3.21	s 3.07	vw 3.04	m 3.05	3.02	m 3.20	vw 2.46
2.190	m 3.11	s 2.17	s 2.15	m 2.99	2.14	s 2.72	m 1.810
1.866	vw 2.88	w 1.850	ew 2.06	s 2.67	1.824	ew 2.58	w 1.536
1.787	w 2.57	m 1.768	s 1.834	s 2.44	1.746	s 2.48	m 1.373
1.548	m 2.27	w 1.530	ew 1.760	w 2.16	1.512	s 2.27	ew 1.319
1.420	m 2.14	vw 1.407	w 1.520	w 2.12	1.382	ew 2.18	ew 1.181
1.384	m 2.025	m 1.368	m 1.395	s 1.800	1.353	vw 1.950	ew 1.045
1.263	m 1.998	m 1.250	ew 1.362	m 1.660	1.234	ew 1.800	ew 1.033
1.191	vw 1.938	ew 1.181	m 1.241	m 1.599	1.164	ew 1.745	
1.094	m 1.911	vw 1.082	m 1.170	ew 1.497	1.069	s 1.607	
1.046	s 1.830	ew 1.035	w 1.077	vw 1.152	1.022	w 1.573	
1.032	s 1.775	w 1.020	w 1.028	vw 1.111	1.008	m 1.481	
.979	w 1.641	vw .967	vw .962	ew 1.057	.957	ew 1.385	
.944	ew 1.551	vw .922	ew .927	ew .972	.923	ew 1.306	
.933	ew 1.422	ew .849	ew .813				
	w 1.206	ew .818	ew .792				
	w 1.186						
	w 1.166						
	ew .944						

⁵ Specimen of the type mineral, kindly sent by Mr. Samuel G. Gordon.

⁷ It is very difficult to obtain a satisfactory pattern with molybdenum radiation. This record is not very good.

26	27	28	29	30	31	32	33	34
Covellite (1, 7, 52) (57, 26, 59)	Berzelianite ⁸ (29, 16)	Rickardite	Bornite (35)	Sodium Chloride	Enargite ⁹ (22, 36)	Emplectite ¹⁰ (32)	Nantokite ¹¹ (69)	Chalcocite ¹² (3, 1, 7)
vw 3.33	3.30	m 3.30	w 3.29	vw 3.25	s 3.23	s 3.22	3.17	m 3.14
w 3.24	2.025	vw 3.10	w 3.15	s 2.814	s 3.09	m 3.11	2.74	vw 2.73
m 3.04	1.727	w 2.78	w 2.81	s 1.990	s 2.86	s 3.04	1.942	w 2.51
s 2.81	1.652	m 2.53	w 2.73	ew 1.696	m 2.23	s 2.33	1.657	m 2.38
m 2.72	1.432	s 2.06	w 2.50	m 1.625	s 1.856	vw 2.24	1.586	s 1.963
w 2.30	1.314	m 1.975	vw 2.18	w 1.407	s 1.730	s 2.16	1.373	s 1.868
ew 2.09	1.282	ew 1.913	vw 2.10	ew 1.291	m 1.592	w 1.951	1.261	w 1.690
vw 2.03	1.170	vw 1.808	s 1.925	m 1.258	w 1.557	w 1.854	1.228	m 1.643
s 1.890	1.102	w 1.703	vw 1.643	m 1.149	vw 1.423	m 1.795	1.122	ew 1.553
m 1.730	1.013	w 1.422	ew 1.575	w .995	w 1.265	s 1.651	1.057	ew 1.509
m 1.555	.954	w 1.399	ew 1.530	w .938	vw 1.218	w 1.558	.972	ew 1.273
vw 1.465		ew 1.337	ew 1.470	w .890	w 1.190	ew 1.446	.929	ew 1.070
vw 1.382		ew 1.296	vw 1.420	w .848	w 1.150	ew 1.368		
w 1.347		vw 1.220	vw 1.369	ew .812	vw 1.130	ew 1.314		
w 1.272		w 1.160	ew 1.260	vw .780	vw 1.070	ew 1.165		
w 1.210		w 1.155	w 1.118	vw .752	w 1.044	ew .996		
m 1.093		vw 1.118	ew 1.055		ew 1.028			
w 1.056		ew 1.031	ew 1.007		vw 1.010			
w 1.014		ew .893	vw .969		w .977			
vw .990		ew .925	ew .925		ew .928			
w .950					vw .896			
ew .893					vw .887			
ew .847					w .865			
					ew .815			

⁸ The writer was unable to obtain specimens of this mineral satisfactory for x-ray analysis. The data listed were calculated from structural data obtained by Hartwig (29), who worked on natural, not artificial, material.

⁹ Specimens labeled famatinite, from the type locality, gave records identical with the above. A spectroscopic analysis, made by G. A. Harcourt, indicated that this material was probably much nearer the enargite end of the series than it was the famatinite end. Frebold (22) reports a record for famatinite which is very different from that of enargite. If famatinite actually exists, as is supposed, in the same crystal system as enargite, and as the opposite end member of an isomorphous series, then it should have a similar record. Apparently Frebold secured an incorrectly identified specimen. W. F. de Jong (36) states that enargite and famatinite are isomorphous, with nearly equal lattices. His patterns of the two are so nearly alike that they are practically indistinguishable. If he also did not have material closer to the enargite end of the series than he supposed, then his results are probably closer to the truth than those of Frebold. It appears, from this work and that of the writer, that if famatinite, with the composition assigned to it, does exist in nature, then it may not be distinguished from enargite by means of *x*-ray powder patterns.

¹⁰ The writer was unable to obtain any wolfsbergite. Hofman (32) has shown it to be isomorphous with emplectite but with a smaller unit cell. Wolfsbergite, therefore, should give a similar pattern to this, but the values of "*g*" should be slightly lower, and intermediate members of the series would show intermediate patterns.

¹¹ Data based on work by Wyckoff and Posnjak (69). Apparently the value of the first line varies down to 3.12 Å.

¹² The writer's results do not agree closely with those of Bateman and Lasky (7). They state that two types of chalcocite occur in nature; one is isometric and one orthorhombic. However, they have not proved that the isometric form is pure Cu_2S , but say that they believe it is. The writer was unable to find any size of unit cell which would satisfy more than 10 of the 15 lines they list for the isometric form. Certainly, if the isometric form does occur in nature, it does not have the same size of unit cell as the isometric form above 200°C., which was determined by Barth (3). The writer's records show lines in each complete record which have been separated by Bateman and Lasky, some being placed in their orthorhombic group, and some in their isometric. Thus, if they are right, it seems that the two forms must generally occur together, intimately intergrown. However, the writer's records also contain lines not listed in either record of Bateman and Lasky, and which do not seem to be due to impurities. The writer's record, as listed here, is in closer agreement with the work of Alsen (1).

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Stannite	Nantokite ¹³ (4)	Sulvanite (22, 36, 55)	Stromeyerite	Bertholite?	Colusite ¹⁴ (71)	Germanite ¹⁴ (37)	Chalcocopyrite (12, 13, 28, 54)
s 3.12	3.12	m 3.11	s 3.10	s 3.10	s 3.06	s 3.06	s 3.03
w 2.71	2.70	w 2.69	s 2.92	vw 2.73	vw 2.66	ew 2.65	w 2.61
ew 2.14	1.910	m 2.41	vw 2.79	vw 2.54	s 1.873	s 1.870	s 1.855
s 1.911	1.630	s 1.903	s 2.59	w 2.33	s 1.598	m 1.597	s 1.586
s 1.634	1.560	w 1.792	m 2.52	w 2.13	ew 1.529	vw 1.322	w 1.515
ew 1.562	1.351	m 1.624	m 2.46	m 1.950	w 1.324	w 1.213	w 1.320
vw 1.358	1.240	ew 1.558	vw 2.33	m 1.906	m 1.218	w 1.080	w 1.294
m 1.240	1.208	vw 1.495	vw 2.19	vw 1.769	ew 1.185	vw 1.017	m 1.205
m 1.107	1.104	w 1.347	m 2.13	vw 1.635	m 1.1086	ew .937	m 1.074
w 1.043	1.041	vw 1.308	ew 2.02	vw 1.551	m 1.019	ew .895	ew 1.010
vw .959	.955	w 1.235	w 1.837	ew 1.172	vw .939	ew .837	vw .930
w .917	.914	ew 1.205	w 1.790	ew 1.060	w .897	vw .892	vw .892
vw .858		ew 1.178	ew 1.635	ew 1.022	vw .838	vw .882	vw .882
ew .828		m 1.098	ew 1.527		ew .808	w .834	w .834
		vw 1.036	ew 1.465		ew .743	ew .802	ew .802
		vw 1.000	ew 1.419			ew .799	ew .799
		vw .952	ew 1.196			ew .759	ew .759
		ew .938				vw .739	vw .739
		vw .911				ew .706	ew .706
		ew .852				ew .698	ew .698
		ew .778				ew .683	ew .683
						ew .647	ew .647
						ew .622	ew .622
						ew .614	ew .614
						ew .606	ew .606

¹³ Data based entirely on the work of Barth and Lunde (4, 5). Apparently the value of the first line varies up to 3.17 Å.

¹⁴ The records for colusite and germanite are indistinguishable, each having the same sized unit cell and a structure similar to that of sphalerite. These are distinguished from sphalerite with ease, since, though similar, the spacings of the lines are very different. Germanite and colusite must be distinguished by their color, the former being pink and the latter buff.

43	44	45	46	47	48	49	50	51
Cuprite (49, 50, 28) (56, 46, 67)	Tetrahedrite ¹⁵ (42, 43)	Schwarzite ¹⁵	Tennantite ¹⁵ (42, 43)	Delafosite	Tenorite (47, 48, 63)	Algodonite ¹⁶ (58, 44, 40)	Whitneyite ¹⁷ (58, 44, 40)	Copper (see below)
vw 3.03	s 3.00	s 2.96	s 2.94	m 2.84	s 2.53	m 2.27	s 2.09	s 2.08
s 2.46	w 2.60	w 2.57	w 2.55	s 2.49	s 2.32	m 2.13	ms 1.82	m 1.810
m 2.13	vw 2.45	vw 2.42	vw 2.40	m 2.22	m 1.865	s 2.00	m 1.29	m 1.273
ew 1.740	vw 2.04	vw 2.02	vw 2.00	m 1.650	w 1.710	w 1.56	m 1.095	m 1.087
m 1.506	vw 1.900	vw 1.872	vw 1.862	m 1.507	vw 1.578	w 1.31	w 1.040	w 1.040
m 1.282	s 1.839	s 1.813	s 1.803	m 1.428	m 1.501	w 1.20	vw .901	vw .901
w 1.230	ew 1.784	ew 1.763	ew 1.749	m 1.332	m 1.410	w 1.12	w .828	w .807
vw 1.065	ew 1.734	ew 1.712	ew 1.700	w 1.289	m 1.370		vw .735	vw .735
w .978	ew 1.687	ew 1.664	ew 1.654	w 1.247	ew 1.302		(8, 51, 52, 70,	(8, 51, 52, 70,
w .952	m 1.568	m 1.547	m 1.537	vw 1.113	w 1.260		34, 53, 17, 65,	34, 53, 17, 65,
w .870	ew 1.502	ew 1.480	ew 1.472	w 1.036	ew 1.155		31, 39, 62, 58,	31, 39, 62, 58,
w .822	ew 1.471	ew 1.452	ew 1.443	vw .988			64, 20, 33)	64, 20, 33)
	ew 1.301	ew 1.282	ew 1.274	ew .962				
	ew 1.243	ew 1.228	ew 1.219	ew .949				
	vw 1.209	ew 1.195	ew 1.185	vw .898				
	vw 1.193	vw 1.176	vw 1.170	vw .853				
	ew 1.122	ew 1.110	ew 1.100	ew .813				
	ew 1.096	ew 1.083	ew 1.075	vw .804				
	vw 1.061	vw 1.048	vw 1.041					
		ew .987						
		ew .944						
		ew .913						
		ew .812						

¹⁵ Machatschki (42, 43) finds that tennantite, the arsenic member of the series, has the smaller unit cell. As antimony replaces the arsenic, or as silver replaces the copper, the size of the unit cell increases. As the cell size is changed by the variation in composition, the powder diffraction pattern varies accordingly in the spacing of its lines. This variation is large enough so that the end members of the series may be identified by their patterns, as may the intermediate members. Schwatzite, the mercurial member of the series, has a record identical to that of the intermediate members, and thus can not be distinguished from them by x-ray pattern alone. This last named mineral seems to give much better pictures, however, than the other members of the group. The record above for tetrahedrite is from a silver rich specimen, and thus is at one extreme of the series. The record for tennantite is from a specimen tested microchemically by Mr. M. Lewis, who reports it to be truly representative of the other end of the series.

¹⁶ This is considered by Ramsdell (58) to be a definite mineral, generally mixed with Cu-As solid solution, but easily distinguishable and identifiable when a good record is obtained. If too much of the Cu-As solid solution (whitneyite) is present, both the algonite and whitneyite records will be recorded. Record and information kindly furnished by L. S. Ramsdell. Machatschki (44) considers this to be a mixture and not a true mineral.

¹⁷ The whitneyite pattern is almost indistinguishable from that of copper. The spacings run about one per cent larger. The lines are rather diffuse because of the distortion of the Cu lattice by the As atoms. Most specimens of either "algonite" or "whitneyite" are mixtures of algonite and the Cu-As solid solution, and may show lines of both. Information and record kindly sent by L. S. Ramsdell.

INDEX 2

Numbers after mineral names refer to the entry number in Index 1, where the complete record may be found.

EXPLANATION

Lines arranged in order of their relative intensity. Records lacking intensity symbols will not be listed here.

. . . . indicates intensity of line is equal or interchangeable.

Increase←-----Intensity-----→Decrease					Mineral	Entry No.
5.40	5.00 2.82 2.75 2.26				Atacamite	2
5.40	4.67	3.69	3.96		Chalcanthite	3
5.20	3.53 3.67	2.52			Azurite	6
5.00	5.40 2.82 2.75 2.26				Atacamite	2
4.67	5.40 3.69	3.96			Chalcanthite	3
4.40	3.83	2.69	2.38		Boleite	7
3.82	4.40 2.69	2.38			Boleite	7
3.69	5.40 4.67	3.96			Chalcanthite	3
3.67	5.20 3.53	2.52			Azurite	6
3.53	5.20 3.67	2.52			Azurite	6
3.52	2.15 1.831				Marshite	21
3.35	1.810 . . . 1.373	1.536			Chrysocolla	25
3.23	1.948	2.28	3.72		Miersite	14
3.23	1.730 . . . 1.856 . . . 2.86 3.09				Enargite	31
3.22	3.11	3.04	2.33		Emplectite	32
3.22	3.04	2.33	2.16		Emplectite	32
3.12	1.911	1.634			Stannite	35
3.11	3.52	1.797			Linarite	9
3.11	3.22 3.04	2.33			Emplectite	32
3.10	2.98	1.751	2.29		Chalcostibite	17
3.10	2.92 2.59				Stromeyerite	38
3.10	1.950	1.906			Bertholite	39
3.09	1.730 . . . 1.856 . . . 2.86 3.23				Enargite	31
3.07	3.21	1.937	1.858		Cubanite	12
3.07	2.17	1.368 . . . 1.768			Eucairite	20
3.07	1.937	1.858	3.21		Cubanite	12
3.06	1.870	1.596			Colusite	40
3.06	1.870	1.592			Germanite	41
3.04	3.22 3.11 2.16				Emplectite	31
3.03	1.855	1.586			Chalcopyrite	42
3.00*	1.837	1.565	1.259		Tetrahedrite	44
2.98	3.10 1.751	2.29			Chalcostibite	17
2.96*	1.831	1.547	2.57		Schwartzite ^a	45
2.94*	1.803	1.537	2.55		Tennantite	46

* Members of a continuous series from 3.00Å to 2.93Å.

^a Intermediate tetrahedrite-tennantite series.

Increase←	Intensity				→Decrease	Mineral	Entry No.
2.93	1.803	1.540	2.54			Tennantite	46
2.92	3.10	2.59				Stromeyerite	38
2.90	2.74					Kröhnkite	4
2.86	1.730	1.856	3.09	3.23		Enargite	31
2.83	3.65	4.98	2.48			Malachite	1
2.82	5.40	5.00	2.75	2.26		Atacamite	2
2.81	1.990	1.258	1.625	1.149		NaCl (salt)	30
2.81	1.890	3.04	2.72			Covellite	26
2.75	5.40	5.00	2.82	2.26		Atacamite	2
2.74	2.90					Kröhnkite	4
2.73	1.763	2.96	2.58	1.980	1.945	Bournonite	8
2.72	2.48	2.27	1.697			Connellite	24
2.67	2.44	1.800	1.599			Penroseite	22
2.59	3.10	2.92				Stromeyerite	38
2.53	2.23	1.865	1.501			Tenorite	48
2.52 ^b	5.35	3.91	2.68	1.740		Brochantite	5
2.51 ^b	3.85	2.66	2.45	1.733		Antlerite	11
2.49	2.84	2.22	1.650	1.507	1.428	Delafosite	47
2.48	2.72	2.27	1.607			Connellite	24
2.47	2.14	1.510	1.287			Cuprite	43
2.44	2.67	1.800	1.599			Penroseite	22
2.33	3.22	3.11	3.04			Emplectite	31
2.32	2.53	1.865	1.501			Tenorite	48
2.29	3.10	2.98	1.751			Chalcostibite	17
2.27	2.72	2.48	1.607			Connellite	24
2.26	5.40	5.00	2.82	2.75		Atacamite	2
2.17	3.07	1.768	1.368			Eucairite	20
2.15	3.52	1.831				Marshite	21
2.09	1.820	1.29	1.095			Whitneyite	50
2.08	1.810	1.273	1.087			Copper	51
2.06	3.30	2.53	1.975			Rickardite	28
2.04	1.878	2.14	1.958			Domeykite	10
2.00	2.13	2.27				Algodonite	49
1.990	2.814	1.259	1.625	1.149		NaCl (salt)	30
1.963	1.868	2.38	3.14			Chalcocite	34
1.925	3.29	3.15	2.81	2.73		Bornite	29
1.911	3.12	1.634				Stannite	35
1.903	3.11	1.624	2.41	1.098		Sulvanite	37
1.890	2.81	3.04	2.72			Covellite	26
1.878	2.04	1.958	2.14			Domeykite	10
1.870	3.06	1.596				Colusite	40
1.870	3.06	1.592				Germanite	41
1.856	1.730	2.86	3.23	3.09		Enargite	31
1.831	3.52	2.15				Marshite	21

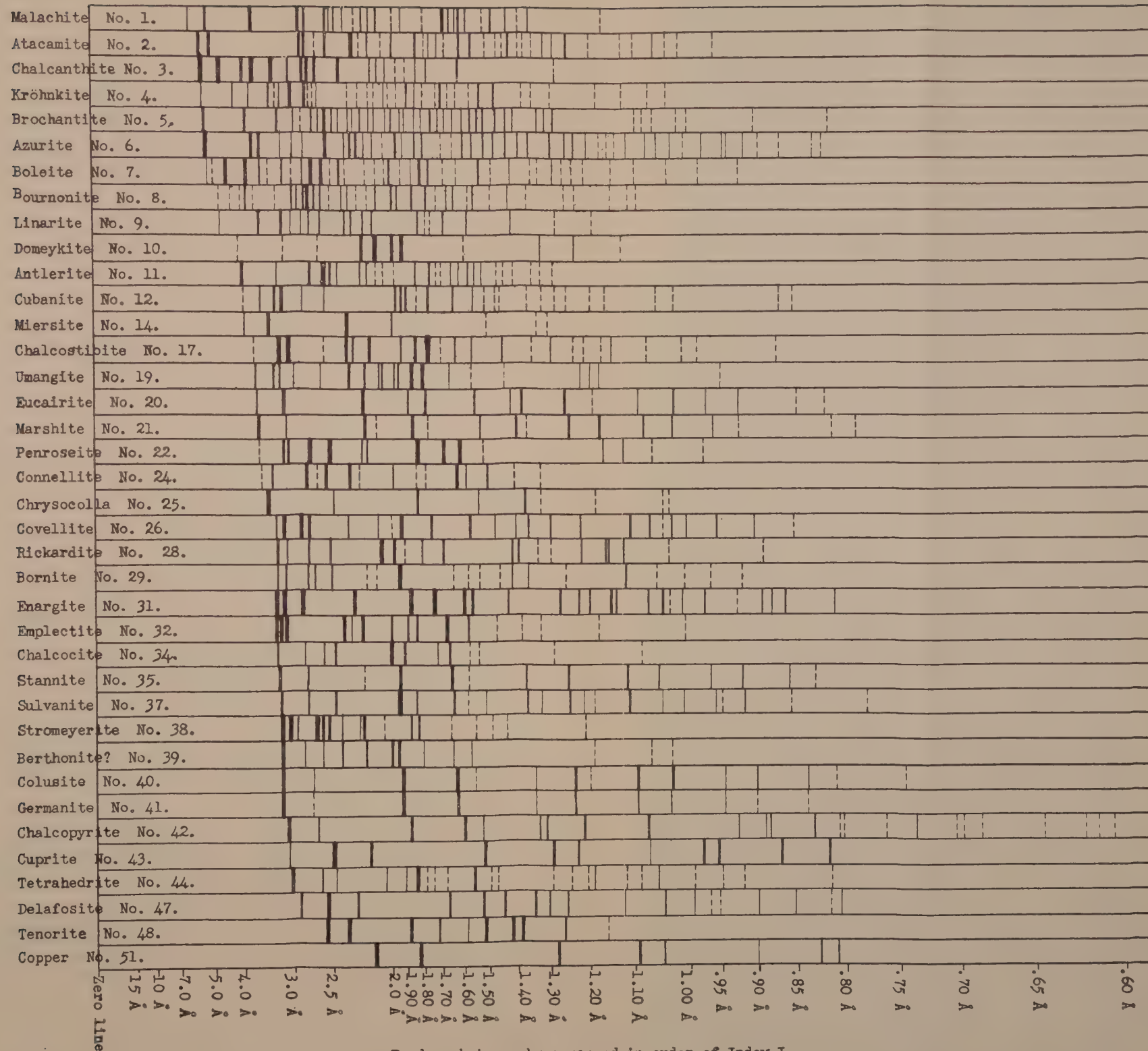
^b These two have nearly identical records.

Increase←	Intensity		→Decrease	Mineral	Entry No.
1.830	1.775	2.27		Umangite	19
1.800	2.67	2.44	1.599	Penroseite	22
1.775	1.830	2.27		Umangite	19
1.751	3.10	2.98	2.29	Chalcostibite	17
1.730	1.856	2.86	3.23	Enargite	31
1.607	2.72	2.48	2.27	Connellite	24

INDEX 3

Minerals arranged alphabetically. Reference to Index 1.

Mineral	Entry No.	Mineral	Entry No.
Algodonite	49	Enargite	31
Antlerite	11	Eucairite	20
Atacamite	2	Famatinitite	31
Azurite	6	Germanite	41
Berthonite	39	Kröhnkite	4
Berzelianite	27	Linarite	9
Boleite	7	Malachite	1
Bornite	29	Marshite	21, 23
Bournonite	8	Melaconite	48
Brochantite	5	Miersite	14
Chalcanthite	3	Nantokite	33, 36
Chalcocite	34	Penroseite	22
Chalcopyrite	42	Rickardite	28
Chalcostibite	17	Sodium Chloride	30
Chrysocolla	25	Schwartzite	45
Colusite	40	Stannite	35
Connellite	24	Stromeyerite	38
Copper	51	Sulvanite	37
Covellite	26	Tennantite	46
Cubanite	12	Tenorite	48
Cuprite	43	Tetrahedrite	44
Delafosite	47	Umangite	19
Domeykite	10	Whitneyite	50
Emplectite	32	Wolfsbergite	32
		(see Emplectite)	



Powder photographs arranged in order of Index I.

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NOTES AND NEWS

AN OCCURRENCE OF NARSARSUKITE IN MONTANA

WILLIAM A. P. GRAHAM,¹ *Ohio State University*.²

During the summer of 1932 an occurrence of a yellow mineral associated with quartz veins cutting a green syenite was noted on the northwest finger of the main stock of East Butte, Sweet Grass Hills, Montana, in the center of Section 24, T 36 N, R 4 E. At some earlier date a shallow prospect pit had been sunk in the syenite at this point.

The main uplift of East Butte was caused by the injection of a Tertiary stock which sharply upturned the Madison limestone, of Mississippian age, and the successively younger beds. From the northwest portion of the stock a finger of syenite extends in a direction N 47° W, cutting through the Madison limestone and the basal portion of the Ellis formation. Several small xenoliths of Madison limestone are still present on the ridge formed by the projecting syenite finger. Dikes of vogesite radiate from the stock for several miles but their relation to the quartz veins is not clear though both seem to be of late magmatic origin.

The narsarsukite was seen only in the quartz veins in the roof rock and upper part of the intrusive. Fresh material was found at the old prospect pit on one of the veins, and was associated with a little galena, alunite, epidote, clinozoisite, apatite, and feldspar. Where the veins cut the syenite the magma had apparently assimilated a block of limestone, for there are shreds and irregular fine-grained aggregates of recrystallized calcite. Many calcite grains separated by other minerals in this section, extinguish together as if a large grain had been mostly replaced. Feldspar, dusty with kaolinite, is the only essential mineral of the original syenite that remains near the veins.

The physical properties of the narsarsukite are as follows: mostly fresh but slightly attacked along cracks, forming an opaque dusty aggregate, perhaps leucoxene; tetragonal (?); prismatic; brittle;

¹ A paper left by Mr. Graham in nearly finished form at the time of his death in 1934.

² Appreciation is here expressed to Mr. C. E. Erdmann of the United States Geological Survey for his invitation to the writer to study the rocks of the Sweet Grass Hills, Montana, in a joint effort to solve their petrologic problems.

cleavages good, 100 and 010;³ irregular fracture along the base; hardness $5.5 \pm$; specific gravity by pycnometer $2.75 \pm$. The inclusions in the slightly weathered material make it impossible to determine the specific gravity more accurately.

Optical characters: uniaxial positive; elongation positive; $\epsilon = 1.653 \pm .003$, $\omega = 1.612 \pm .003$; pleochroic, ϵ -honey yellow, ω -colorless.

A chemical analysis of the Montana narsarsukite by R. B. Ellestad was made possible by a grant from the Graduate School of Ohio State University. This is tabulated beside an analysis of the same mineral from the type locality in Greenland as recorded by Dana.⁴

TABLE 1
ANALYSES OF NARSARSUKITE

	Montana	Greenland
SiO ₂	62.30	61.63
Al ₂ O ₃	0.32	0.28
Fe ₂ O ₃ } FeO }	3.46	6.30
MgO	0.46	0.24
MnO	—	0.47
CaO	0.18	—
Na ₂ O	15.31	16.12
K ₂ O	0.41	—
F	—	0.71
H ₂ O	Not det.	0.29
TiO ₂	16.80	14.00
Total	99.24	100.04

The optical and chemical data on this mineral have been checked and supplemented by Dr. W. T. Schaller and Miss Jewell J. Glass of the United States Geological Survey and through their kindness the following tabulation may be made to call attention to certain peculiarities of narsarsukite. On the basis of differences between the Montana data and the records of older work on the original

³ This change in the designation of cleavage faces is reported in recent x-ray studies; Waters, B. E., and Amberg, C. R., *X-ray Study of Narsarsukite: Am. Mineral.*, vol. 19, pp. 546-48, 1934; and an earlier paper by Gossner and Strunz, *Zeit. Kryst.*, vol. 82, p. 151, 1932.

⁴ Dana's System of Mineralogy, p. 73, Appendix 2, 1914 ed., analysis by Christensen.

TABLE 2
DETERMINATIONS BY W. T. SCHALLER ON RECENTLY ACQUIRED NARSARSUKITE

	Montana	Greenland
FeO	0.47	0.19
Fe ₂ O ₃	3.13	6.36
ε	1.655	1.628 to 1.633
ω	1.609	1.606 to 1.608
Biref.	.046	.022 to .025

material,⁵ it seemed desirable to test Greenland narsarsukite, and some was contributed by the United States National Museum, by the Philadelphia Academy of Natural Science, and by Columbia University. Some yellow transparent grains gave constant values, whereas brownish grains, apparently altered and less transparent, gave variable and slightly higher indices and birefringence.

TABLE 3
DIFFERENCES IN NARSARSUKITE SPECIMENS

Montana			Greenland		
Honey yellow, pleochroic Prismatic Cleavages good, 100, 010 Hardness 5.5			Colorless, yellow, and brown, non- pleochroic Tabular, rarely cubic Cleavage perfect, 110? Hardness 7-7.5		
ε	ω	Biref.	ε	ω	Biref.
1.653	1.612	.041	1.630	1.609	.021*
1.653	1.608	.045	1.625	1.604	.021
1.654	1.608	.046	1.625	1.604	.021
1.655	1.609	.046	1.630	1.609	.021
			1.628	1.605	.023
			1.636	1.607	.029
			1.633	1.608	.025
			1.628	1.606	.022

* Larsen and Berman, *Bulletin U. S. Geol. Survey*, **848**.

⁵ Dana's System of Mineralogy records as results of the original description: ε=1.5842, ω=1.5532. These seem to be incorrect.

The Montana mineral agrees with the original in being tetragonal, with two cleavage directions, uniaxial, positive, transparent to translucent. Both have a specific gravity about $2.75 \pm$. The pattern (x -ray) of the narsarsukite from Narsarsuk in the Columbia University collection agreed with that of the Montana material according to a report from Professor P. F. Kerr of Columbia University to Dr. Schaller.

Note that whereas the values of the lower index are about the same in the two occurrences, the index of the extraordinary ray of the Montana mineral is so much higher than that of the Greenland mineral that the birefringence is doubled. Clearly the mineral has a range of indices and birefringence suggesting differences in composition at least as great as those shown in Table 1. High index and birefringence are commonly suggestive of high iron in mineral series, but are here found in the Montana samples which have low iron and a low ratio of ferric to ferrous oxides. Whether the differences in titanium and in sodium are sufficient to account for the different optical constants is not clear.

ON THE APPLICATION OF DETERMINANTS TO CRYSTALLOGRAPHY

J. D. H. DONNAY, *Johns Hopkins University.*

Our distinguished colleague of the University of Florence, Professor P. Aloisi, published a short note under the above title in the May 1935 issue of this journal, in which he reminds us that priority in the matter of introducing determinants in crystallography belongs to Quintino Sella (1857). Professor Aloisi calls attention to this historical point on the occasion of the publication of my paper on the use of determinants in crystallography.¹ He makes the statement that it does not appear from my article whether I consider the application of determinants to crystallography as something new or not. He adds that "in any case the author does not mention anything to that effect."

I was well aware that I was not the first to apply the theory of determinants to crystallography, for this method used in Italian university courses and treatises on morphological crystallography can be found in textbooks of many other lands as well, although I am sorry to say it has not been currently adopted in America. My

¹ *Am. Mineral.*, vol. 19, pp. 593-599, 1934.

intention, certainly, was not to try to deprive Quintino Sella of his well established right of priority. It never occurred to me that anyone could conceive that I was offering "something new" by recalling, as a necessary introduction for the rest of my paper, the condition for tautozonality of three faces in the form of the co-efficient determinant. It has been known in that form for nearly four score years.

I did not intend to claim credit for having introduced determinants in crystallography, but stated in two different places the portions of my article I believed to be new. (1) In the first paragraph (page 593), I said: "The application of the elementary properties of determinants leads, moreover, to several new zonal relations"; (2) page 595, fourth paragraph: "The following fact has not been mentioned, as far as the writer is aware. . . ." The theorems which appear below this statement (labelled from A to D), including the rule given on page 598, are the only contributions which I thought (and still think) to be original.

If my presentation has lacked the necessary clarity to avoid misinterpretation, I deeply regret the fact. Possibly I should have quoted in the introduction the footnote which the French master, G. Friedel, wrote on page 896 of his "Groupements cristallins":

"On ne croira pas, je l'espère, que je pense dire ici des choses nouvelles. Mais on verra plus loin combien ces notions élémentaires ont été perdues de vue et qu'il n'était pas inutile de les rappeler."

OPALIZED SPHERULES FROM UTAH?

A. E. ALEXANDER, *Buffalo Museum of Science.*

The Buffalo Museum of Science recently acquired a number of interesting opalized spherules. They were found in Utah, but the exact locality did not accompany the acquisition.

Fully 90% of the mineral grains are uniform in size, the spherules measuring about one millimeter in diameter. The drawing by Miss Dorothy Mosher shows the marked degree of sphericity.

Of particular interest is the presence of a nucleus in each grain, which may be either a sand particle or a small rock fragment. Petrographic analysis of the material surrounding the core showed this substance to be opal.



FIG. 1. Opalized spherules with sand grain or rock particle core. Actual size 1 mm.

Not knowing the locality from which these spherules were obtained, no conclusions as to origin can be drawn. However, the presence of opal is suggestive of hot spring deposition. Dr. Hyrum Schneider, mineralogist, and Professor A. L. Crawford, metallurgist, of the University of Utah, kindly examined the material for the writer. An artificial origin is suggested by Professor Crawford, who is of the opinion that these grains *might* be formed from sodium silicate used in flotation mills. The spherules found in mill tailings however were devoid of nuclei.

Any information that anyone might have as to the exact locality from which these spherules might have come and as to the environment under which they were formed, would be greatly appreciated.

PROCEEDINGS OF SOCIETIES

PHILADELPHIA MINERALOGICAL SOCIETY

Academy of Natural Sciences of Philadelphia, May 2, 1935

Dr. Gillson, president, called to order a stated meeting of the Philadelphia Mineralogical Society, with 43 members and 30 visitors present.

Members on the field trip to Vanartsdalen's quarry on Sunday, April 7, reported finding graphite, titanite, wernerite, phlogopite, apatite, hornblende, microcline, salite, pyrrhotite, coccolite, and blue quartz; and at Finney's quarry: garnet, blue quartz, zircon, and traces of malachite. Other trips reported were: Easton (aragonite and asbestos); Mineral Hill (actinolite); Bridgeport (malachite, sphalerite); Parlin and South River, N. J. (petrified wood, pyrite, amber on pyrite and lignite); Stanley County, N. C. (limonite pseudomorph after pyrite).

Mr. Charles R. Toothaker addressed the society on "Recollections of Mineral Collecting," in which he related in intimate fashion his experiences while in the employ of Dr. A. E. Foote, one of the greatest of all mineral collectors. He told how the business was established in 1876, the methods of acquiring specimens and collections, and how they were distributed to famous private collectors and museums. Many of the famous finds of superlative specimens in Guanajuato, Sardinia, Laurium, Meteor Crater, and elsewhere, were described.

W. H. FLACK, *Secretary*

NEW YORK MINERALOGICAL CLUB

CONDENSED MINUTES OF MEETINGS HELD FROM OCTOBER 1934 TO MARCH 1935

October Meeting

The New York Mineralogical Club held a regular meeting on October 17, 1934, in the Academy Room of the American Museum of Natural History. The meeting was called to order by President Gilman S. Stanton.

The Club learned with sorrow of the deaths since our last meeting of the following members:

Mme. Marie Sklodowska Curie, of Paris, France, on July 4, 1934; reported by Pres. Gilman S. Stanton.

Mr. James Walker, of Brooklyn, N. Y., on July 25, 1934; reported by Past Pres. George E. Ashby.

Mrs. Richard Durkee, of New York, N. Y., reported by her brother, Mr. C. W. Hoadley, on Oct. 17, 1934.

Mr. Erwin F. Gross, of Brooklyn, N. Y., reported by the Post Office Department on Sept. 25, 1934.

Memorials were read by Mr. H. R. Lee for Mme. Curie and by Mr. George E. Ashby for Mr. Walker. These were ordered spread upon the minutes and copies forwarded to the families of the deceased.

MEMORIAL FOR MARIE SKLODOWSKA CURIE

The New York Mineralogical Club at the meeting of Oct. 17, 1934, records on its minutes with regretful sorrow the death of its notable and esteemed honorary member Madame Marie Sklodowska Curie on July 4, 1934.

Her gracious acceptance in person of membership on May 17, 1921, after her election at this Club's April 20, 1921, meeting did us the greater honor. The membership certificate then presented to her stated in part: "The New York Mineralogical Club . . . desiring to express its fullest appreciation of the eminence attained by her in the field of science, and her transcendent service to humanity through the discovery of radium . . . and her many and great contributions to the science of radioactivity, hereby confers upon MARIE SKLODOWSKA CURIE honorary membership. . . ."

A cablegram of condolence was sent her daughter, Madame Irene Curie-Joliot, on July 5 and the death recorded by this Club in both the *Herald Tribune* and the *New York Times* of July 6, as follows:

CURIE, Marie. A great loss to science and humanity is recorded with sorrow and shared in the passing of our distinguished member.

NEW YORK MINERALOGICAL CLUB, Gilman S. Stanton,
President

Well knowing that we can add nothing to what the world has acclaimed, it is sorrowfully ordered that this record be spread upon the Club's minutes and copies forwarded to the daughters of Madame Curie with the sincere sympathy of the Club.

NEW YORK MINERALOGICAL CLUB, by Gilman S. Stanton,
President
Daniel T. O'Connell,
Secretary

MEMORIAL FOR JAMES WALKER

James Walker, an esteemed member of the New York Mineralogical Club since 1892, died July 25, 1934, at the age of 91, after a long illness.

He had lived in Brooklyn for many years and was a veteran of our Civil War, N. Y. 62nd Zouaves, and a member of Grant Post No. 327 G.A.R. He was born in Belfast, Ireland, and never had married.

An expert in time devices, he was enthusiastic and thorough in his varied interests in mineralogy and microscopy. He was beloved by all who knew him.

His minerals had been given to the Brooklyn Children's Museum; his microscopical apparatus to the Microscopical Society, and his horological library to the Seth Thomas Clock Co., with which he was for many years associated.

This Club was represented at his funeral services by President Stanton and Vice-President Varni, and a floral tribute which has been gratefully acknowledged by his cousin, Miss Rebecca Miller.

Mr. Walker's portrait is the bearded one in plates 120 and 123 in Manchester's "The Minerals of New York City and Its Environs."

NEW YORK MINERALOGICAL CLUB, by Gilman S. Stanton,
President
Daniel T. O'Connell,
Secretary

The meeting was turned over to the members of the Club, who reported on their summer prospecting experiences and collections.

Mr. Arthur Montgomery described his experiences in the Thomas Range, Utah, and Devil's Head, Colorado.

Miss Catherine Schroder described her sojourn in Paradise Valley, Washington.

Mr. Charles W. Hoadley described his New England collecting and exhibited chrysoberyl from Hartford, Conn., and beryl from Norway, Me.

Mr. Stephen Varni exhibited the Mt. Mica green tourmaline discovered by Loren B. Merrill of Paris, Maine, considered Maine's finest gem—422 carats without a flaw.

Mr. Grenzig exhibited a prehnite stalactite from Paterson, N. J.

Mr. Ernest Weidhaas exhibited Mcgovernite, zincite, and ruby corundum from Franklin, N. J., and a sand spike from Laguna Beach, California.

November Meeting

The New York Mineralogical Club held a regular meeting in Room 201 of the American Museum of Natural History on Wednesday evening, Nov. 21, 1934. President Gilman S. Stanton called the meeting to order.

Mr. Clifford Frondel was introduced by President Stanton, and addressed the Club on the subject of "Selective Incrustation and Selective Coloration of Crystals." (See Frondel, *Selective Incrustation of Crystal Forms*, *American Mineralogist*, July, 1934, vol. 19, No. 7, pp. 316-329.

December Meeting

The New York Mineralogical Club held its regular meeting in Room 201 of the American Museum of Natural History on Dec. 19, 1934.

The speaker of the evening was Dr. Daniel T. O'Connell of the Department of Geology of the College of the City of New York, whose topic was the "1934 Rainbow Bridge—Monument Valley Expedition."

The speaker described the geological work of the expedition, which was also interested in archaeological excavations and biological studies, in the far western desert area known as the Navajo Indian Reservation in northeastern Arizona. The base camp of the expedition was at Kayenta, Arizona, at the Wetherill Ranch. Motion pictures and slides showed the expedition's trip across the United States, with stops at Gettysburg, Natural Bridge, Va., and Carlsbad Caverns. One of the important discoveries made by the speaker was the finding of a skeleton of a plesiosaur lying in place on the Mancos shale of Black Mesa, near Kayenta, Arizona,—the first one to be found in Arizona. A white friable mineral found with carbonaceous shale beds near the base of the Mancos shale of Black Mesa, in the same vicinity, has been identified as goslarite $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$. This is a new locality for goslarite. Dr. O'Connell also exhibited a natural dyed Navajo blanket rug colored by a uranium black dye made from carnotite.

January Meeting

On the evening of January 16, 1935, the New York Mineralogical Club held its regular meeting with an attendance of 103. The meeting was called to order by President Gilman S. Stanton.

President Stanton introduced the speaker of the evening, Mr. L. H. Bauer, Chief Chemist of the New Jersey Zinc Co., who addressed the Club on "Minerals from Franklin and Sterling Hill, N. J." There have been reported 146 minerals from the vicinity of Franklin, N. J., but only three of these are of economic importance:—Franklinite, willemite, and zincite, although in the early mining at Sterling Hill, calamine and chalcophanite were found. The chief waste minerals are calcite, garnet-variety andradite, tephroite, rhodonite, sphalerite, pyroxenes, amphiboles, feldspars, micas, and spinel. Mr. Bauer described the process of separating the franklinite from the crude ore. He also pointed out the folly of depending on colors in identifying minerals, using as an example the willemite, which is green from Franklin, N. J., brown from Sterling Hill, and also occurs blue and black. The importance of fluorescence was revealed in the many ways this phenomenon has been made use of at the mine.

Mr. Frederick I. Allen described an interesting experiment with franklinite. He stated that after solution of franklinite in hydrochloric acid and precipitation of the sulphides of Fe, Mn, and Zn in alkaline solution, these sulphides could be successively decomposed by progressive acidification—the black FeS disappearing first, the flesh colored MnS next, leaving the pure white ZnS visible. The changes of color and exhibition of the three bases in succession make an interesting experiment, although not useful as a means of separation.

February Meeting

A regular meeting was held on the evening of February 20th, 1935, with a record-breaking attendance of 147.

President Stanton introduced the speaker of the evening, Professor Alfred C. Lane, of Tufts College, Medford, Mass. He addressed the Club on the subject of "Radioactive Minerals—Measure of Geologic Time." In radioactive substances we have the disintegration of atoms, which is an example of paroxysms occurring regularly. The helium bullets shot off by disintegrating atoms within a zircon crystal for example, will produce the discoloration of biotite, in which it may be imbedded, producing the so-called pleochroic halos which provide a measure of geologic time called the Helium Method, which involves studying the halos under a highpower microscope. The uranium-lead and thorium-lead ratios based on careful chemical analysis of uranium minerals to discover what proportion of their uranium has changed to radioactive lead, provides another measure of geologic time.

Uraninite from Wilberforce, Ont., by this method has been given an age of 1046 million years since the mineral formed. Pitchblende from the Canadian Great Bear Lakes locality, 1277 million years. Dr. Hugh S. Spence, who investigated this latest great radium source for the Canadian government, was present at the meeting and provided a number of lantern slides showing the uranium vein which has been traced for three miles, to supplement the lantern slides shown by Prof. Lane. The various radioactive minerals and their characters were described in detail and representative specimens of each were exhibited.

March Meeting

A regular meeting of the New York Mineralogical Club was held on the evening of March 20th, with an attendance of 117.

Mr. Frederick I. Allen reported for the Nominating Committee as follows: For President: Gilman S. Stanton. For 1st Vice-President: Dr. Horace R. Blank. For 2nd Vice-President: H. R. Lee. For Secretary: Dr. Daniel T. O'Connell. For Treasurer: Miss Catherine Schroder. For Delegate to the New York Academy of Science: Mr. George E. Ashby.

President Stanton introduced the speaker of the evening, Dr. W. F. Foshag, Curator of Mineralogy, United States National Museum, Washington, D. C., who addressed the Club on the subject of "Collecting Saline Minerals in the Mojave Desert and Death Valley," illustrated by lantern slides.

DANIEL T. O'CONNELL.
Secretary